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PERFORMANCE TESTS OF HIGH SPEED ZRV OIL SKIMMER

BY

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FOR

U. S. ENVIRONMENTAL PROTECTION AGENCY
OIL AND HAZARDOUS MATERIALS SIMULATED ENVIRONMENTAL TEST TANK
LEONARDO, NEW JERSEY 07737

FINAL REPORT

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16. Abstract

A self-propelled catamaran oil skimmer developed by the USCG capable of recovering oil from a water's surface was tested at the U.S. EPA OHMSETT facility. The skimmer employed an endless composite sorbent belt processed between the catamaran hulls to recover oil. The tests were designed to determine the effect that various parameters (skimmer speed, oil viscosity, oil thickness, wave conditions, etc.) have upon oil recovery performance. The skimmer was towed through oil slicks at various speeds in different wave conditions as it was operated to collect oil. The collected fluid was quantitatively analyzed to determine the device's oil-to-water recovery ratio (recovery efficiency), oil recovery rate and thoroughness of slick removal (throughput efficiency).

The device proved capable of good throughput efficiency in all wave conditions (up to 0.7 m confused seas) at all the tow speeds tested (1 to 6 knots). Throughput efficiencies of 80 to 90% in calm water were common with all the oils tested. The performance of the full-scale skimmer agreed well with the results from the smaller prototype tested in 1976. The successful development of this skimmer provides a significant advance in oil spill recovery capability and technology. The concept used in this oil skimmer can be employed at speeds greater than those tested. Two oil slick converging systems were tested with the skimmer to effectively double the sweep width of the skimmer. Additional tests were conducted to determine vessel resistance and motion in waves and to assess the buildup of potentially explosive vapors within the oil recovery system.

17. Key Words OIL SKIMMER OIL SPILL OLEPHILIC BELTS OIL RECOVERY ZERO RELATIVE VELOCITY ZRV BOATS	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

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PREFACE

This report presents the results of a performance test program performed on the U.S. Coast Guard Zero Relative Velocity (ZRV) oil skimmer. Mason & Hanger-Silas Mason Co., Inc., performed this work under Contract No. 68-03-2642 with the U.S. Environmental Protection Agency for the United States Coast Guard, during the period 8 September through 13 October 1979.

CDR W.W. Becker, of the U.S. Coast Guard Office of Research and Development, served as Project Officer during this program. M.K. Breslin of Mason & Hanger-Silas Mason Co., Inc. served as Project Engineer. S.H. Cohen of Hydronautics, Inc. served as Project Engineer for the Air Jet Boom tests and as the co-author of the analysis of the Air Jet Boom and Water Jet portions of the tests. The efforts of LT Robert Ramsay of the U.S. Coast Guard Shipyard for his help in the preparation of the device for testing and his help throughout the test program are gratefully acknowledged. The USCG Atlantic and Gulf Strike Team/NSF personnel who operated the device and assisted in other testing duties are sincerely thanked. Acknowledgment is gratefully given to the USCG Research and Development Center for instrumentation support and providing the Box-Behnken analysis, vapor detection analysis, roll response analysis and tow force analysis sections of this report. Invaluable advice and assistance, during the tests, was given by M.G. Johnson of Mason & Hanger-Silas Mason Co., Inc., while serving as Test Director and Lead Technician for the test. Mr. J. Ward of Shell Development Co. and Mr. A.C. McClure of Alan McClure Associates, Inc. are sincerely thanked for their previous work and advice during the tests.

Additional reports on the development and testing of the USCG ZRV oil recovery vessel are available to the public through: The National Technical Information Service, Springfield, Virginia 22161.

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LIST OF CONVERSIONS

METRIC TO ENGLISH

To convert from	to	Multiply by
Celsius	degree Fahrenheit	$t_f = (1.8)t_c + 32$
joule	erg	1.000 E+07
joule	foot-pound-force	7.374 E-01
kilogram	pound-mass (lbm avoir)	2.205 E+00
metre	foot	3.281 E+00
metre	inch	3.937 E+01
metre^2	foot^2	1.076 E+01
metre^2	inch^2	1.549 E+03
metre^3	gallon (U.S. liquid)	2.642 E+02
metre^3	litre	1.000 E+03
metre/second	foot/minute	1.969 E+02
metre/second	knot	1.944 E+00
metre^2/second	centistoke	1.000 E+06
metre^3/second	foot^3/minute	2.119 E+03
metre^3/second	gallon (U.S. liquid)/minute	1.587 E+04
newton	pound-force (lbf avoir)	2.248 E-01
watt	horsepower (550 ft lbf/s)	1.341 E-03
Kilopascals	pounds/ft	4.133 E-04

ENGLISH TO METRIC

centistoke	metre^2/second	1.000 E-06
degree Fahrenheit	Celsius	$t_c = (t_F - 32)/1.8$
erg	joule	1.000 E-07
foot	metre	3.048 E-01
foot^2	metre^2	9.290 E-02
foot/minute	metre/second	5.080 E-03
foot^3/minute	metre^3/second	4.719 E-04
foot-pound-force	joule	1.356 E+00
gallon (U.S. liquid)	metre^3	3.785 E-03
gallon (U.S. liquid)/minute	metre^3/second	6.309 E-05
horsepower (550 ft lbf/s)	watt	7.457 E+02
inch	metre	2.540 E-02
inch^2	metre^2	6.452 E-04
knot (international)	metre/second	5.144 E-01
litre	metre^3	1.000 E-03
pound force (lbf avoir)	newton	4.448 E+00
pound-mass (lbm avoir)	kilogram	4.535 E-01
pounds/in^2	Kilopascals	4.788 E+01

LIST OF ABBREVIATIONS AND SYMBOLS

cSt --Centistoke
^{o}C --Degrees Centigrade
Dist. --Distribution
Eff --Efficiency
Ext. --Extension
^{o}F --Degrees Fahrenheit
Fwd. --Forward
HC --Harbor Chop Wave
IFT --Interfacial Tension
LEL --Lower Explosive Level
LWH --Length-Width-Height
MERL --Municipal Environmental Research Laboratory
No. --Number
ORR --Oil Recovery Rate
RE --Recovery Efficiency
SD --Shakedown test
SFT --Surface Tension
Spd. --Speed
stbd --Starboard
TE --Throughput Efficiency
Thk. --Thickness
USCG --United States Coast Guard
US EPA --United States Environmental Protection Agency
u/w --underwater
ZRV --Zero Relative Velocity

cm --centimeter
dia --diameter
cm^2 --square centimeter
ft --foot
gpm --gallons per minute
hp --horsepower
hr --hour
in --inch
kg --kilogram
kt --knot
lb --pound
m --meter
m^3 --cubic meter
mm --millimeter
pp --pages
ppt --parts per thousand
psi --pounds per square inch
secs or s --second
% --percent

Following are used in Appendix D

X_i --symbols for independent variables
Y --symbol for dependent variables
R2 --multiple correlation coefficient
F --F-test statistical analysis

D.O.F.1	--degrees of freedom in numerator
D.O.F.2	--degrees of freedom in denominator
X_1	--oil viscosity
X_2	--tow speed
X_3	--slick thickness
Std. Dev.	--Standard deviation
B	--coefficients for equation predicting device performance from test conditions

Following are used in Appendix H

L_s	--oil lost in wake of skimmer
Q_1	--initial oil slick volume
Q_2	--skimmer entrance oil volume
Q_3	--skimmer recovered oil volume
W_B	--skimmer recovered water volume
L_B	--oil volume lost by boom
δ	--slick thickness distribution
E_s	--independent skimmer thruput efficiency
$E_{s/B}$	--skimmer/boom thruput efficiency
E_B	--boom diversion efficiency
E_R	--oil recovery efficiency
t_o	—uniform slick distribution
t	--distorted slick distribution
V	--surface current velocity
α	--air jet impingement angle
ℓ	--air jet nozzle throat
h	--air jet nozzle height
p	--air jet internal air pressure
θ	--air jet boom deployment angle
υ	--air jet maximum velocity
σ	--air jet induced current depth
P	--air jet pump inlet pressure
Q	--air jet flow
g	--air compressor flow
p	--air jet boom pressure
A.J.	--air jet boom
W.J.	--water jet boom
C	--calm water
HC	--harbor chop
Indep.	--skimmer used independent of air or water jet booms

Following are used in Appendix G

W_{wave}	--wave frequency
H_{wave}	--wave amplitude
W_{ZRV}	--ZRV skimmer frequency
P_{ZRV}	--ZRV skimmer pitch amplitude
A_{ZRV}	--ZRV skimmer acceleration amplitude
P_{wave}	--maximum wave slope
A_{wave}	--wave acceleration amplitude
L_{wave}	--wavelength
L_{ZRV}	--ZRV skimmer length
B_{ZRV}	--ZRV skimmer beam

INTRODUCTION

The United States Coast Guard (USCG) has developed a high speed oil recovery vessel (skimmer) to operate in rivers, bays, and protected harbors. The skimmer was designed to meet specific goals set forth by the USCG (Appendix A). It was built at the USCG shipyard in Curtis Bay, Maryland and tested at the United States Environmental Protection Agency's (U.S. EPA) Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) (Appendix B). The tests climax a three year program of design, planning, and building a full-scale skimmer designed by Shell Development Company and A.C. McClure Associates. The oil recovery machinery of the full-scale skimmer was based upon a machinery mock-up designed and built by Shell Development Co. in 1976. This report is based upon data from roughly 200 tow tests conducted at OHMSETT on the skimmer (Appendix C) during September and October 1979.

The Shell mock-up was not a vessel but a frame housing belt drive and oil recovery machinery. The system drove one 2-ft wide sorbent belt when it was tested at OHMSETT in 1976.[1] The final skimmer design consisted of a catamaran vessel with two 3.5-ft wide endless sorbent belts running between the hulls (Figures 1, 2, 3, and 4). The belts were a sandwich composite of Astroturf and polypropylene belt which were fed from the front of the device at a rate approximately equal to the vessel's forward speed. They contacted the oil slick, retained the oil and then gave it up when they were drawn aboard the rear of the skimmer and processed through scrapers and wringers. When the speed at which the belt moved through the wringer matched the vessel's forward speed there was no relative movement between the belt and the oil slick it was laying on (an analogy to a caterpiller or tank tread could be used). Hence, the name Zero Relative Velocity or ZRV skimmer was derived.

---

[1] Ayers, R.R., and J.M. Ward. A Zero-Relative-Velocity Belt Skimmer, Stage II-Confirming Tests and Prototype Design. CG-D-23-77, U.S. Department of Transportation, United States Coast Guard, Office of Research and Development, Washington, D.C., 1977. 153 pp.

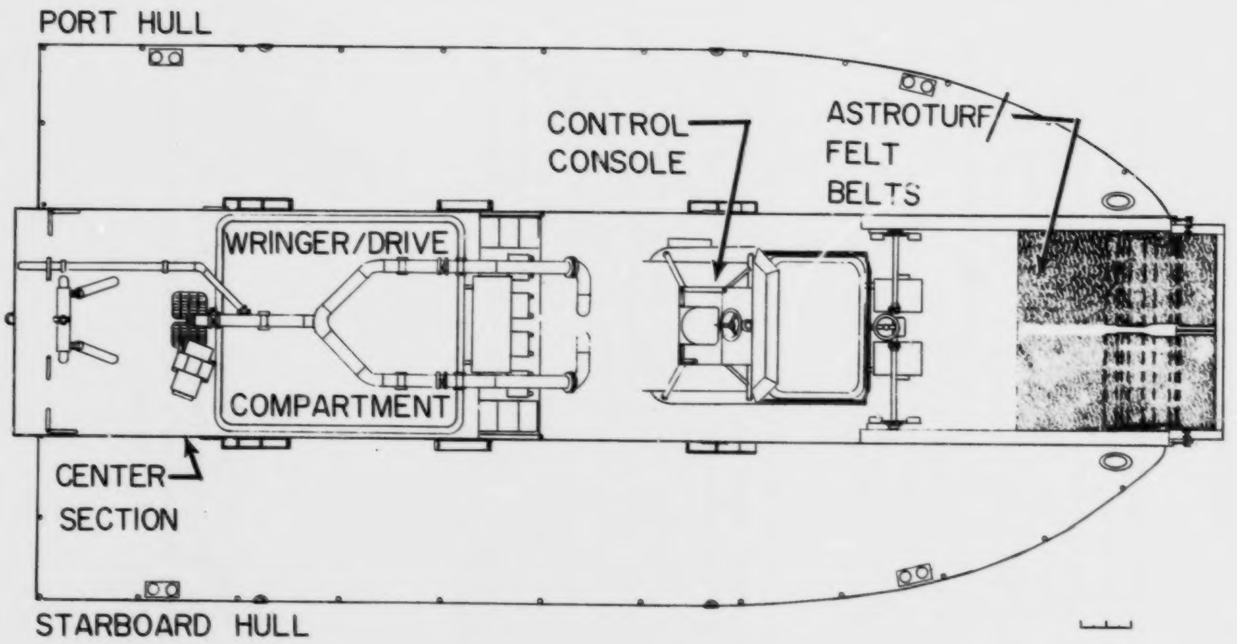

PORT HULL
CONTROL CONSOLE
ASTROTURF FELT BELTS
WRINGER/DRIVE COMPARTMENT
CENTER SECTION
STARBOARD HULL

FIGURE 1. PLAN VIEW OF ZRV OIL SKIMMER.

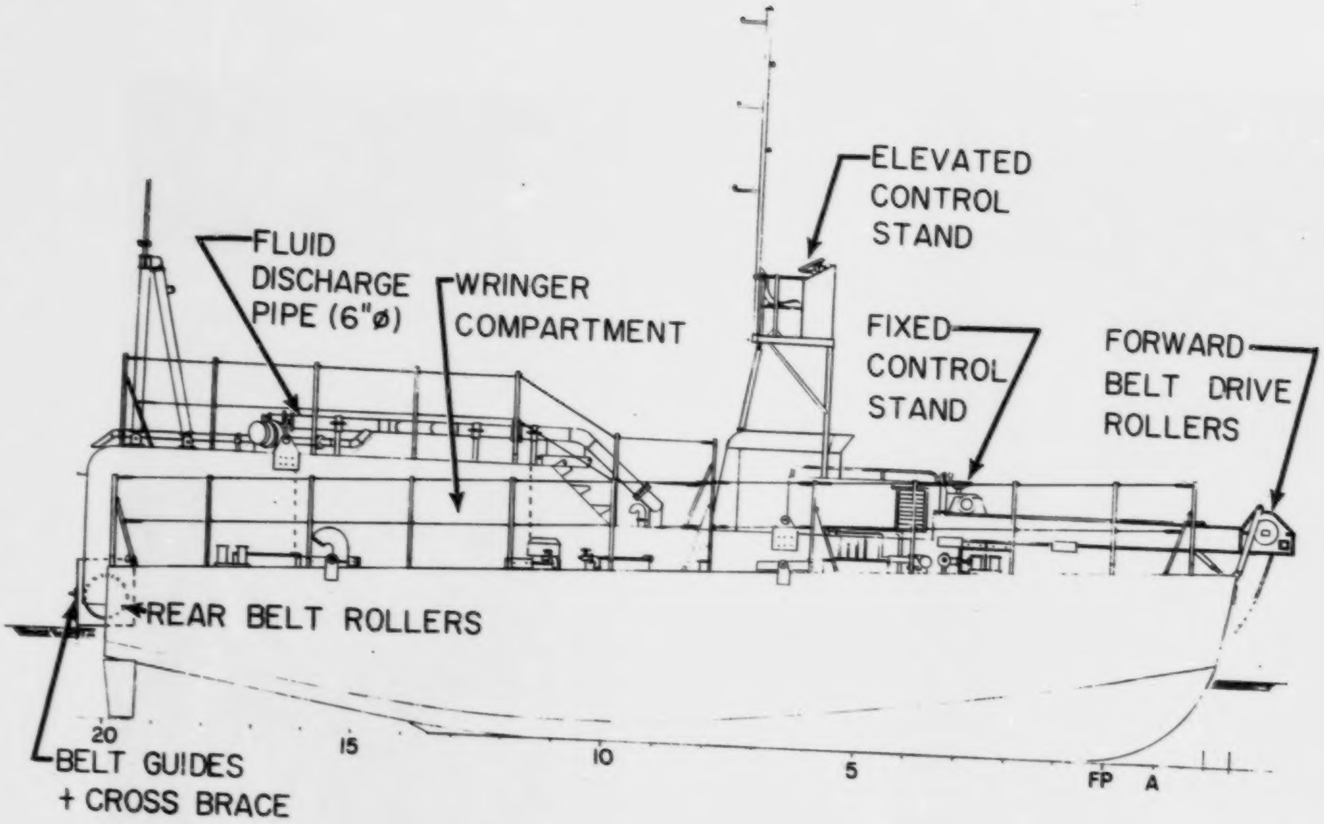

FLUID DISCHARGE PIPE (6"ø)
WRINGER COMPARTMENT
ELEVATED CONTROL STAND
FIXED CONTROL STAND
FORWARD BELT DRIVE ROLLERS
REAR BELT ROLLERS
BELT GUIDES + CROSS BRACE
20
15
10
5
FP
A

FIGURE 2. SIDE VIEW OF ZRV OIL SKIMMER.

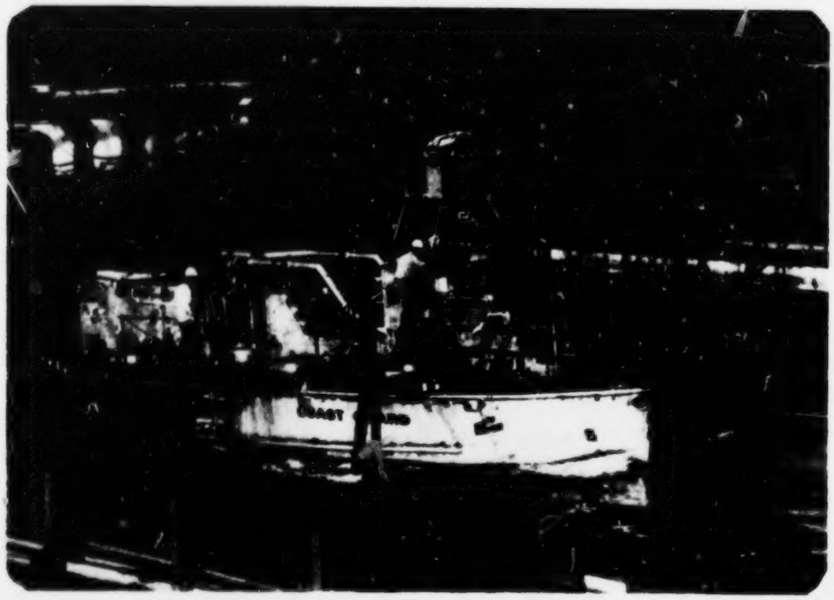


FIGURE 3. USCG ZRV SKIMMER DURING A CALM WATER TEST.

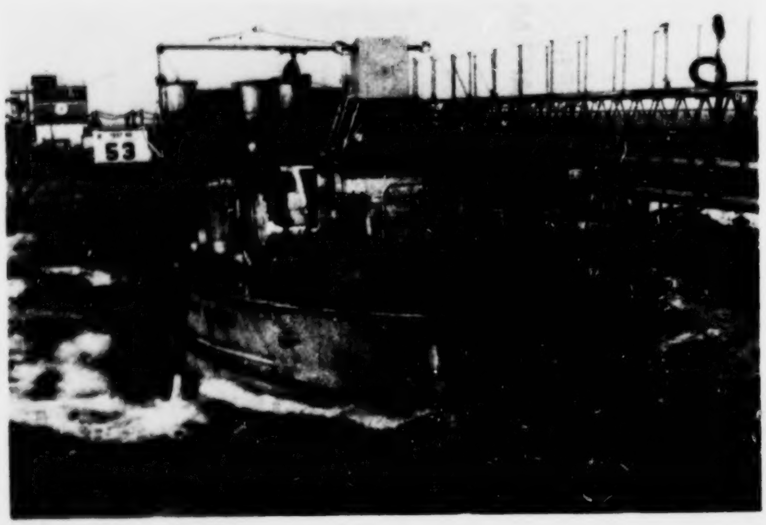


FIGURE 4. USCG ZRV SKIMMER DURING A HARBOR CHOP TEST.

DEVICE DESCRIPTION

The USCG ZRV Oil Skimmer is a further development from a machinery mock-up system designed and developed by Shell Development Company, Inc.[1] Its purpose is to recover oil in a fast current environment in rivers, bays, and moderately calm coastal waters. The skimmer measures 45 ft long, 22 ft wide, 7 ft keel to deck amidship with 3.6 ft draft. It weighs 63,000 lb assembled. Designed to allow for overland truck transport, the vessel was constructed in three sections--two catamaran hulls and the center belt processing unit. Each hull weighs 16,500 lb and the center section weighs 30,000 lb. The main control console area extends 9 ft above the waterline. A collapsible elevated control tower and light mast extend the height to 25 ft above the waterline. A collapsible stern mounted A-frame employed for towing an oil storage bag extends 19 ft above the water line.

Three Detroit Diesel 6V53 naturally aspirated engines power the skimmer. An engine in each pontoon hull drives a fixed-pitch propeller enabling the skimmer to operate at speeds up to 10 knots. These engines drive generators to provide electrical power to storage batteries for auxiliary functions. (Note: These engines were not used during the OHMSETT tests). The center section engine drives hydraulic pumps providing power for the wringers, forward drive rollers, oil transfer pumps, and fire pump. The center section operates independently of the rest of the vessel.

The three engines and the functions they power are controlled from an instrument station on deck. The vessel and machinery controls are manual except for the belt speed which can be automatically controlled. Vessel controls are duplicated in the elevated control station. This station, which swings down for storage, provides an eye of about 16 feet above waterline to give a better view of the approaching oil slick. Underway, a helmsman can steer from the elevated station while a crewman monitors oil recovery from the deck console.

The principle of oil recovery operations lies in processing two continuous 3.5 ft wide, 126 ft long, sorbent belts down between the catamaran hulls at approximately the same velocity as the vessel is traveling forward. The belts are oleophilic and thus sorb oil from the water's surface as the vessel passes. They are drawn up from the water over drums in the rear of the vessel, scraped and then squeezed in a series of rollers positioned around perforated drums. The belts are then routed over powered rollers in the fore of the vessel back onto the oil slick (Figure 5). The forward powered rollers pull the belts from the wringer sections and ensure low tension in the belts as they blanket the oil slick. A spring tensioned guide is positioned behind the belts in the front of the skimmer to ensure the belts contact the water's surface close to the bows (Figure 6). This belt hold-down device can be engaged or retracted using a pneumatic cylinder.

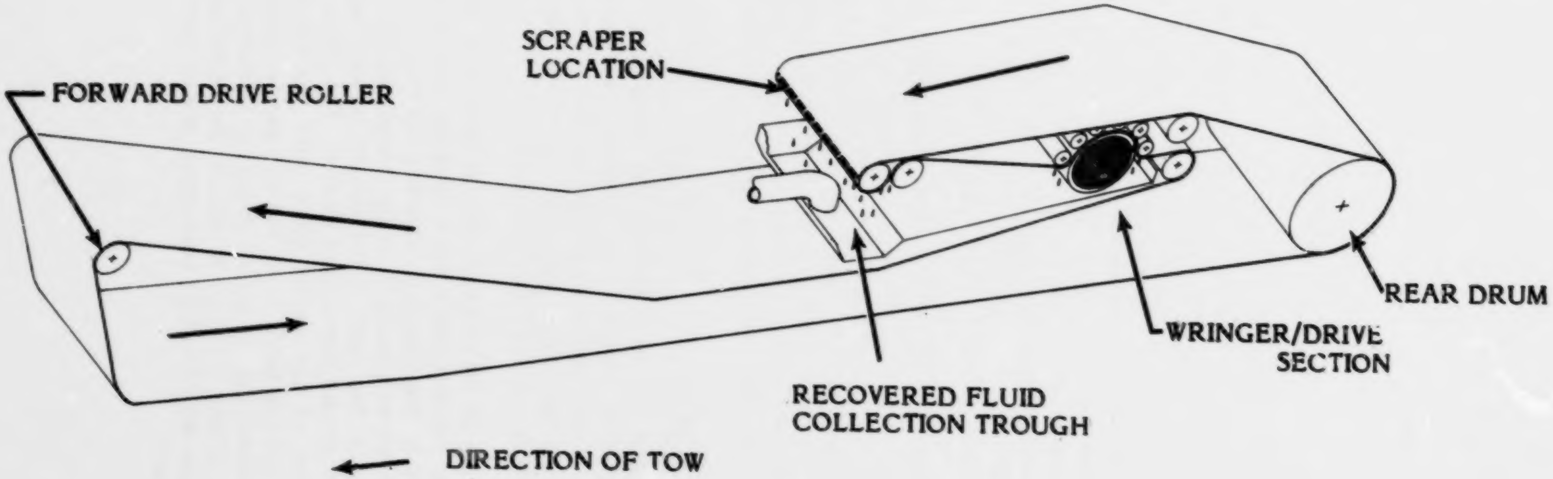

SCRAPER LOCATION
FORWARD DRIVE ROLLER
REAR DRUM
WRINGER/DRIVE SECTION
RECOVERED FLUID COLLECTION TROUGH
DIRECTION OF TOW

FIGURE 5. ISOMETRIC VIEW OF INDIVIDUAL BELT PATH THROUGH THE ZRV SKIMMER.

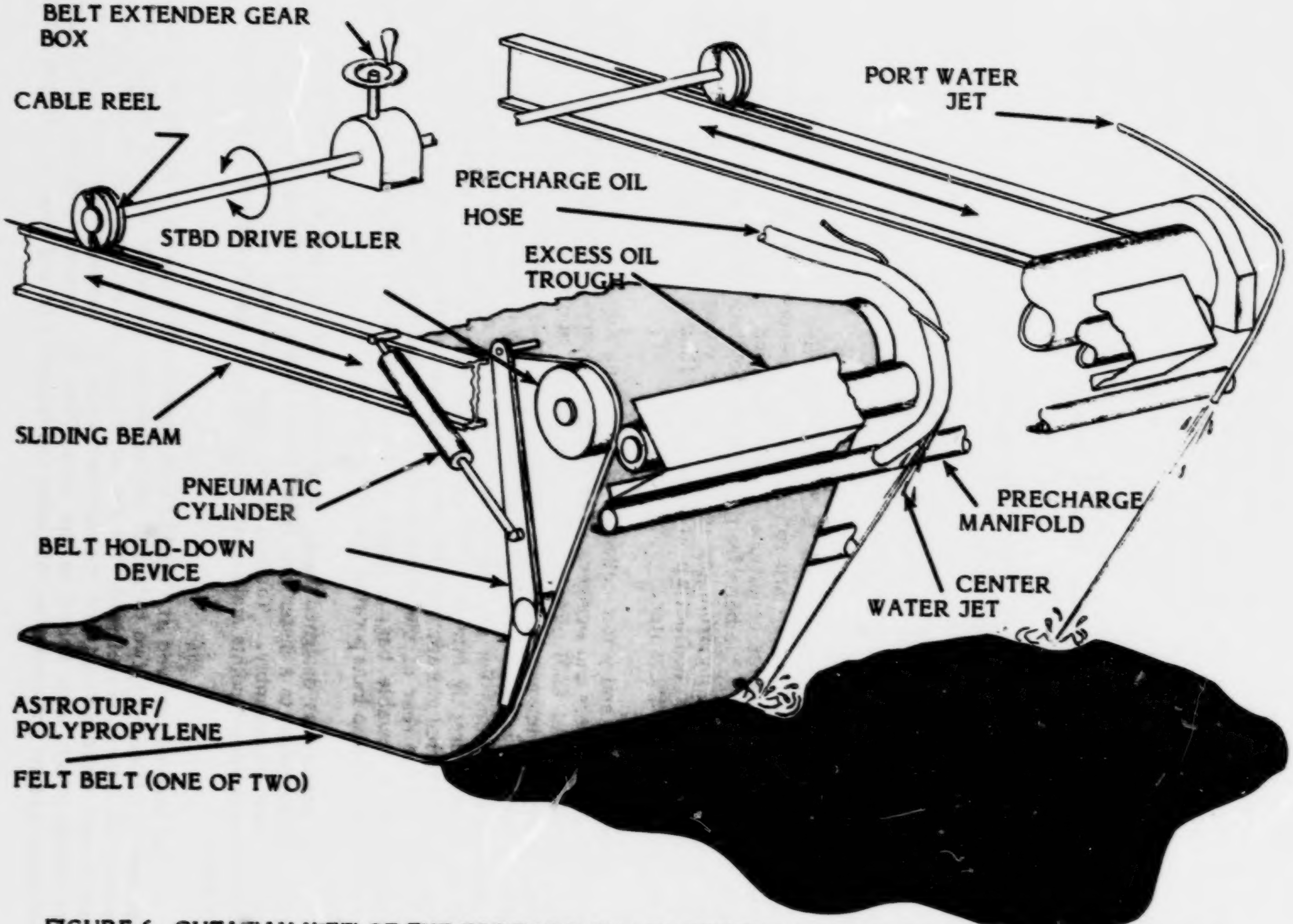

BELT EXTENDER GEAR BOX
CABLE REEL
STBD DRIVE ROLLER
SLIDING BEAM
PNEUMATIC CYLINDER
BELT HOLD-DOWN DEVICE
ASTROTURF/ POLYPROPYLENE
FELT BELT (ONE OF TWO)
PRECHARGE OIL HOSE
EXCESS OIL TROUGH
PORT WATER JET
PRECHARGE MANIFOLD
CENTER WATER JET

FIGURE 6. CUTAWAY VIEW OF THE FORWARD END OF CENTER SECTION OF THE USCG ZRV SKIMMER. (ONLY ONE BELT SHOWN FOR CLARITY)

The belts are made in a sandwich construction of one layer of ½-inch thick polypropylene felt between two layers of an artificial turf material (Figure 7). The turf material is the same as used in sports playing fields (Astroturf). In order to meet the design specifications (Appendix D) the skimmer had to be able to recover both heavy viscous oils and lighter, non-viscous oils. Astroturf proved to be an excellent sorber of viscous oils while the felt recovered the non-viscous oils. The Astroturf does not prevent the lighter oils from reaching the felt and protects the felt from being ripped by the machinery which wrings, scrapes, and propels the belts. Each of the two belts was made up of two lengths about 50 ft and 75 ft long. They were joined using an alligator clip and pin arrangement to ensure a flexible joint. Saturated with water, the belts sink. However, freshly wrung belts are buoyant and so follow the surface of the water during oil recovery operations.

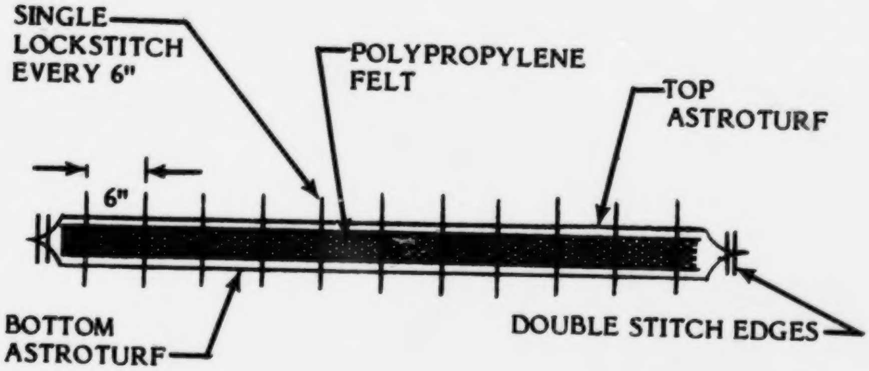
Each of the two wringer assemblies (Figure 8) consists of a number of small rollers partially surrounding a perforated drum. A solid 0.31 in thick endless neoprene belt rides around the rollers and serves as a backing for one side of the squeezing operation. The oil recovery belt enters between the perforated drum and neoprene belt and is squeezed as it travels through consecutively smaller passages between the belt and drum. The wringer assemblies are powered to help drive the belt through the system.

The tautness of the sorbent belts is controlled using the forward roller extension mechanism. The forward rollers can be extended or retracted to improve performance under certain conditions. The extension option was utilized during testing mainly to prevent the belts from becoming too slack during wave tests or high speed runs and thus lifting from the rear drums far enough to contact the rear belt guide cross brace. Such contact would cause sorbed fluid to be scraped from the belt and dumped back onto the water.

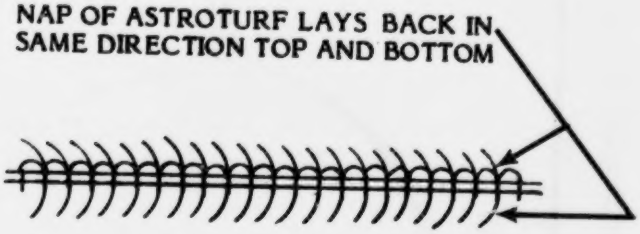
Recovered oil and water collect in a sump amidship after being removed from the belt by the scrapers and wringers. Two 600-gpm rotary-type positive displacement pumps (Tuthill Model 660) pick up the collected oil and send it to either onboard storage or external temporary storage. Being hydraulically powered, the pumps can be driven so that the transfer rate can match the recovery rate and ensure a continuous oil recovery operation. For small spills or final cleanup operations in larger spills, oil may be pumped directly into the 1000 gallon storage tank located in each hull. For larger spills, external storage must be used. By proper valving, the oil is directed from the pumps off the rear of the skimmer via a 6 in diameter line. This line could be connected to a towable bag, a barge or stationary tank. Provision for dumping unwanted fluid is also incorporated into the piping system.

The vessel was designed to be disassembled quickly and easily for truck or airlift transportation to a distant oil spill. Fitted lifting sling arrangements facilitate assembly and disassembly. Tapered pins, angle brackets, A-frame supports and protected attachment points make positioning the hulls against the center section easy and sure.

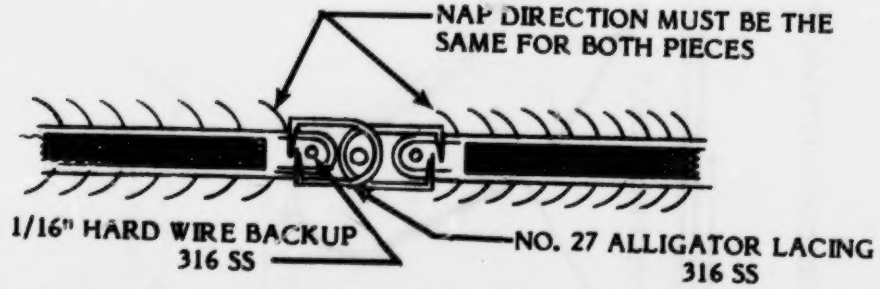
The skimmer arrived at OHMSETT on three flatbed trucks. One 70-ton crane was used to offload the two hulls and center section and place them in position for assembly on a level, gravel yard. The center section was set upon the three A-frame "saw horses" which arrived with the skimmer while the pontoon hulls rested on their own stands which were bolted to the hulls. The port pontoon hull was lifted and positioned against the center section using the tapered pins and housings. It was then


SINGLE LOCKSTITCH EVERY 6"
POLYPROPYLENE FELT
TOP ASTROTURF
6"
BOTTOM ASTROTURF
DOUBLE STITCH EDGES

BELT CROSS SECTION THROUGH WIDTH


NAP OF ASTROTURF LAYS BACK IN SAME DIRECTION TOP AND BOTTOM

EDGE VIEW OF BELT


NAP DIRECTION MUST BE THE SAME FOR BOTH PIECES
1/16" HARD WIRE BACKUP 316 SS
NO. 27 ALLIGATOR LACING 316 SS

LONGITUDINAL CROSS SECTION THROUGH JOINT

FIGURE 7. ZRV BELT CONSTRUCTION - SCHEMATIC.

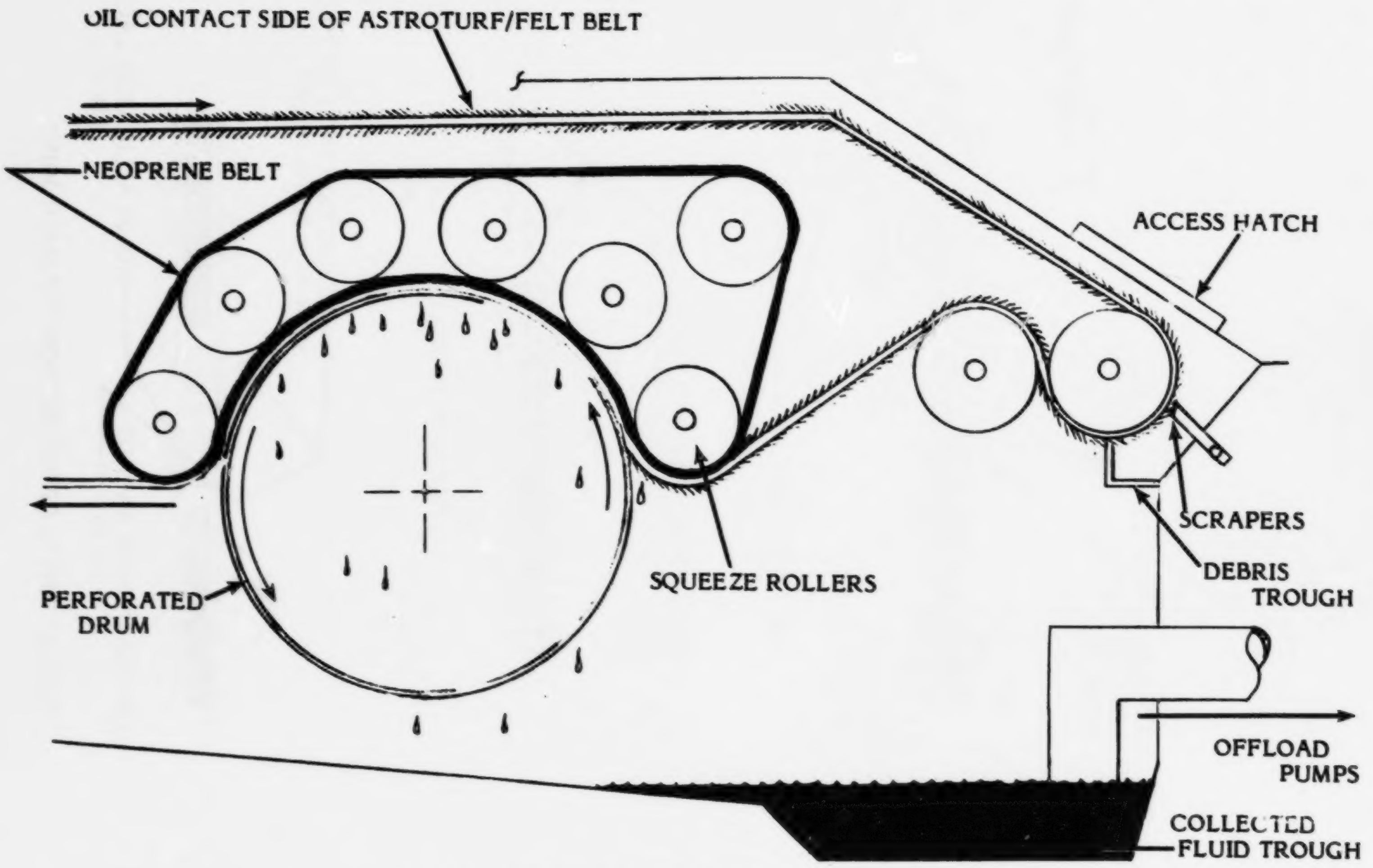

OIL CONTACT SIDE OF ASTROTURF/FELT BELT
NEOPRENE BELT
ACCESS HATCH
SCRAPERS
DEBRIS TROUGH
SQUEEZE ROLLERS
PERFORATED DRUM
OFFLOAD PUMPS
COLLECTED FLUID TROUGH

FIGURE 8. SIDE VIEW OF ASTROTURF/FELT BELT WRINGER.

bolted to the center section. The same was done with the starboard pontoon. The assembly was accomplished in six hours by three men who had not previously worked with the device and one 70-ton crane with its two-man crew. The crane crew did not have to help with anything except lifting the pieces. Helpful directions were obtained from the USCG Yard via telephone.

Skimmer Modifications

During the test program at OHMSETT, several areas of possible device improvement were noted and worked upon. The major modifications are listed here. The work performed was of a temporary nature and the U.S. Coast Guard shipyard will be replacing the temporary fixtures with permanent ones.

A roller which supported the composite belt directly prior to entering the wringer area was removed, because the fluid-laden belt was losing oil and water as it contacted the roller. The fluid was falling upon freshly wrung belt as it left the wringer assembly. The absence of the roller did not adversely affect belt travel.

A thin-wall trough was made to catch fluid which came from the belts as they were driven through the forward rollers. Left unchecked, the fluid would have fallen on the oil slick and disturbed and entrained the oil. Since the belts must contact oil in order to sorb it, any entrainment would decrease device performance. The captured fluid was diverted out the sides of the trough onto the water outboard of the hulls (Figure 8).

Three water jets constructed from small (0.2 in dia.) tubes, were positioned at the bow of the skimmer and directed vertically downward (Figure 6). One was directed so its water stream would impact directly in front of and between the two belts. The other two were directed to impact in front of the two bows. The water jets parted the oil slick where they hit without entraining oil. This pushed oil into the paths of the belts which would have otherwise floated untouched between the belts or along the hulls. The water jet concept has been tested and developed for this purpose at OHMSETT.[2, 3]

A 6-in diameter flexible hose, 6 ft long, was clamped onto the end of the topside engine exhaust of the center section. This served to extend the exhaust below the waterline and thus muffle the engine noise considerably. Since the vessel used a water-cooled exhaust system the exhaust had to be periodically seen to determine if water was still flowing. The flexible hose served this purpose also by flipping up out of the water occasionally to show exhaust fumes and cooling water.

TEST DESCRIPTION

The skimmer was placed in the test tank using two 70-ton cranes and placed between the main and auxiliary bridges facing South (Figures 9 and 10). It was towed from its fairleads using a yoke and single attachment point on the main bridge. A force transducer was placed at the single attachment point on the main bridge to measure tow force on the skimmer (Appendix D). The vessel was also secured to the auxiliary bridge with lines coming from port and starboard stern bitts.

The onboard oil handling system was arranged to discharge off the rear of the skimmer. A 6-in diameter flexible hose carried the collected fluid from the device to the auxiliary bridge where it was collected in translucent barrels. The fluid level in the barrels was measured, the water drained, and then measured again. The remaining fluid was mixed and a sample taken to determine oil/water composition. Between the skimmer piping and the flexible hose a discrete sampling connection was placed in the line. This consisted of a 2 ft long, 6 in diameter pipe with a 0.5 in perforated tube running into it and across its diameter perpendicular to the direction of flow. A valve and flexible tubing were connected to the small pipe. When fluid was being offloaded from the skimmer the valve could be opened and a sample of what was being offloaded could be taken. Such samples were taken during the tests, and the results were plotted vs. time to see if a steady state condition had been achieved. All collected fluids handling, barrel sampling and oil content analysis was performed by the OHMSETT chemistry laboratory personnel.

After the rigging operations were completed, the skimmer was towed down the tank at increasing speeds to test the security of the tie lines and equipment arrangement. Following the "dry run" shakedowns, oil shakedowns were begun. Oil was distributed from the main bridge using an overflow weir manifold. A splashplate was located beneath the manifold to catch the overflow and allow the oil to even out before it hit the water. A piece of cloth extended from the edge of the splashplate to the water's surface and provided a smooth transition from the splashplate to the water. This arrangement was intended to present a smooth, even oil slick to the skimmer.

The oil slick width was maintained using a pair of vertically directed water jets, one on each side of the oil distribution manifold. By regulating the flow through the 0.75 in diameter pipe nozzles the surface current produced by the jets could be controlled. The impact points of the jets were about 1.5 ft outside of the east and west sides of the oil slick. The current produced by the jets diminished to almost nil by the time the ZRV reached the oil slick so there was no interference with the oil skimmer.

The test matrix was designed around a Box Behnken analysis of the data (Appendix E). The analysis called for three different values in each of three unrelated independent variables. These would form three levels in each of the three planes of the Box Behnken representation. Tow speed, oil slick thickness and oil type were the three independent variables. The three tow speeds chosen were 2, 4, and 6 knots.

FIGURE 9. USCG ZRV SKIMMER BEING CRANED INTO THE U.S. EPA TEST TANK (SEPT. 1979).

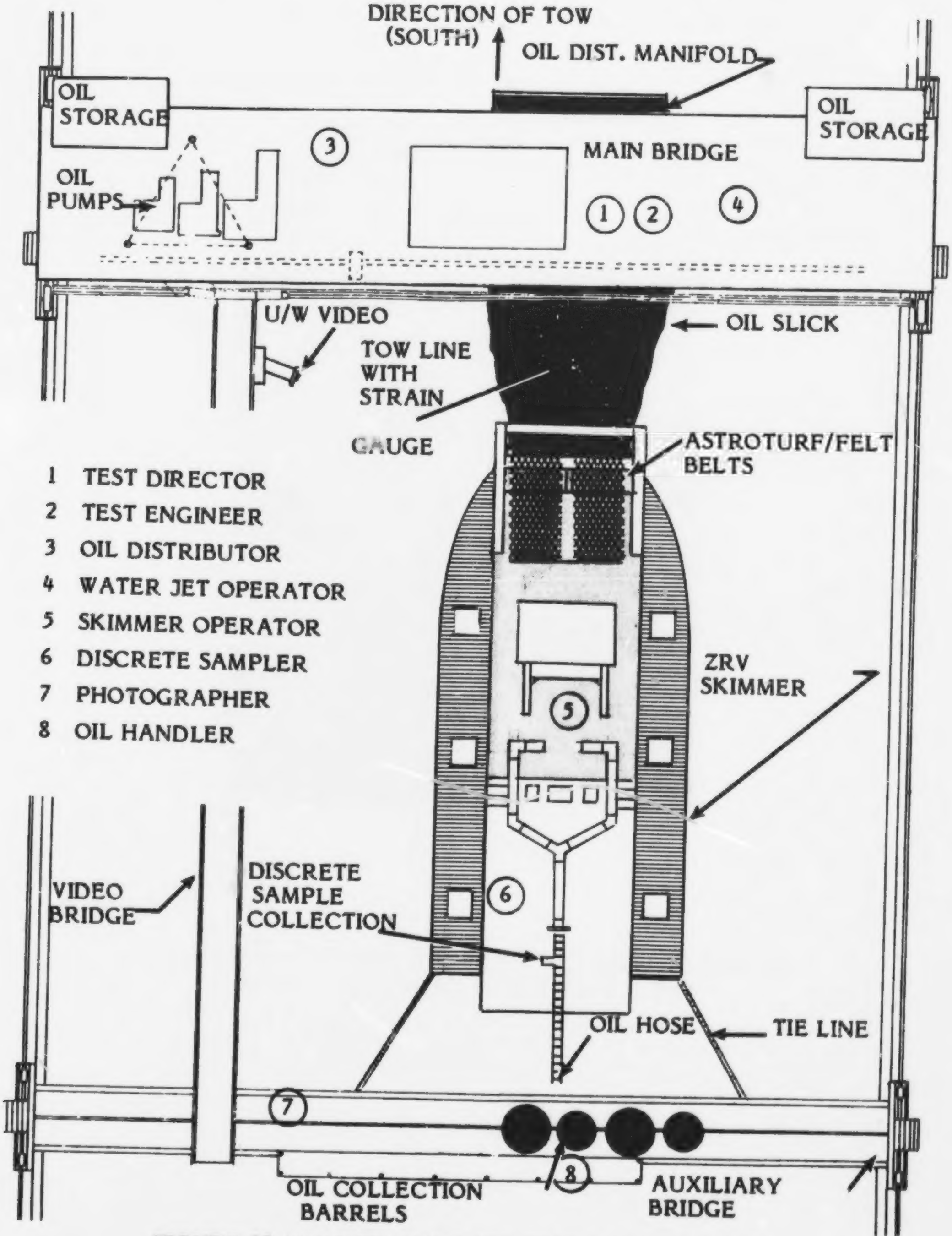

DIRECTION OF TOW
(SOUTH)
OIL DIST. MANIFOLD
OIL STORAGE
OIL STORAGE
③
MAIN BRIDGE
OIL PUMPS
① ②
④
U/W VIDEO
OIL SLICK
TOW LINE WITH STRAIN GAUGE
ASTROTURF/FELT BELTS
1 TEST DIRECTOR
2 TEST ENGINEER
3 OIL DISTRIBUTOR
4 WATER JET OPERATOR
5 SKIMMER OPERATOR
6 DISCRETE SAMPLER
7 PHOTOGRAPHER
8 OIL HANDLER
ZRV SKIMMER
⑤
VIDEO BRIDGE
DISCRETE SAMPLE COLLECTION
⑥
OIL HOSE
TIE LINE
⑦
⑧
OIL COLLECTION BARRELS
AUXILIARY BRIDGE

FIGURE 10. USCG ZRV SKIMMER TEST ARRANGEMENT.

These evenly spanned the range of possible tow speeds. The oil slick thicknesses chosen were 1, 3, and 5 mm. These thicknesses were determined to span the sorbent belts' capacity. The oil types were light, medium, and heavy (Appendix F), which spanned a great deal of the range of oils normally enountered in oil spills. To ensure that each test was comparable to another, a set of procedures was developed and followed for each tow test (Table 1).

TABLE 1. USCG ZRV TEST PROCEDURES

1. All people attend their correct stations.
2. Alert bridge operator and photo/video department as to test number, speed, etc.
3. Obtain the desired wave conditions for testing.
4. Place correct test number in sign on auxiliary bridge.
5. Start the ZRV engines and bring the hydraulic pressure to the desired level.
6. Move all oil from the path of the skimmer.
7. Set the oil distribution system for the desired rate.
8. Apply the oil precharge to the sorbent belt when belts begin moving.
9. Raise the skimming booms on the bridges.
10. Start the tow and bring the sorbent belts up to speed. Start the offloading pumps.
11. Begin oil distribution when the desired test speed is reached. Continue oil distribution for 300 feet down the tank.
12. Collected fluid is to be continuously offloaded to the auxiliary bridge during the test.
13. Discrete sampling is to commence as soon as fluid flows from the skimmer to the collection barrels. Samples will be taken once every 20 seconds for one knot tests, once every 10 seconds for two knot tests, once every 7 seconds for three and four knot tests and once every five seconds for every five and six knot tests. Continue discrete sampling until fluid flow from the ZRV to the collection barrels ceases.
14. The bridge personnel will signal the skimmer operator when the end of the oil slick encounters the device. Continue towing at the test speed for 50 feet and then slow the bridges to a stop.
15. After the end of the slick contacts the belts, stop the sorbent belts after both alligator lace hinges on one belt have passed over the forward rollers.

(Continued)

TABLE 1. (Continued)

16. Stop the ZRV offloading pumps when the onboard collection sump is empty and fluid no longer is being pumped to the auxiliary bridge barrels.

17. Lower the bridge skimming booms and skim the tank surface to the north to prepare for the next test.

18. Using firehoses, pump water into the sump and then start the offloading pumps again to clear the lines of oil. Offload into the collection barrels until clean water exits the oil hose outlet on the auxiliary bridge.

During the oil recovery tests with light oil a hydrocarbon "sniffer" was used by USCG personnel to determine if the possibility of an explosion hazard could develop in the skimmer. The results of the tests are presented in Appendix G.

Towards the end of the test program, two oil slick herding devices were tested in an effort to effectively widen the sweep of the skimmer. The first employed pressurized air to move the oil slick. The concept was developed by Hydronautics, Inc. for the U.S. Environmental Protection Agency.[4] The second employed vertically directed water jets to induce a surface current and thus move the oil slick. This system was developed by Mason & Hanger-Silas Mason Co., for the U.S. Environmental Protection Agency. The tests and results are presented in Appendix H.

Following the oil recovery tests the vessel was moored perpendicular to the longitudinal axis of the tank using light lines fore and aft. A series of waves were produced by the OHMSETT wave generator and the vessel's reaction to those waves was recorded. The data was analyzed by the USCG Research and Development Center, Groton, Connecticut (Appendix I).

DISCUSSION OF RESULTS

DATA

The data results are interpreted by calculating and analyzing three values: Throughput Efficiency (T.E.), which is the amount of oil the skimmer recovered divided by the amount of oil it encountered; Recovery Efficiency (R.E.), which is the percentage of oil in the fluid which the skimmer picked up; and Oil Recovery Rate (O.R.R.) which is the amount of oil the skimmer recovered divided by the time required to recover it. Many tow tests were duplicated for data assurance reasons. The maximum values of RE, ORR, and RE from such tests were used in the graphs presented in this section. These values represent the possible performance capability of the skimmer. Since some tow tests were not duplicated and testing in a tow tank has limitations, the skimmer may be capable of even better performance than the tests indicate.

TE was determined from the oil collected in the barrels on the auxiliary bridge.

$$\text{TE} = \frac{\text{Oil in barrels}}{(\text{Oil distributed})(\text{Percentage encounter})}$$

Percentage encounter was estimated by observers on the main bridge during the test.

RE was determined from the discrete samples taken from the oil discharge hose on the rear of the skimmer and from collection barrel samples. The discrete sample results were plotted vs. time (Figures 11 and 12). A value which appeared to depict a reasonable RE for the system under the conditions tested was selected. Consideration was given to RE build up and the short test time. For example, if the RE climbed quickly and leveled off for the rest of the test a value close to the level portion of the graph was selected. If the RE continued to climb throughout most of the test, a value near the top of the curve was selected. The theory behind this was that in actual oil recovery conditions the skimming operations would be continued on much longer than in the tank test and the RE would remain near the value at which it leveled off during the test. The values derived from the curves were then compared to the percentage of oil in the oil collection barrels. The greater value was chosen as the RE for that test. Since a steady state condition was often not reached during a test run the RE values listed in this report should not be considered maximum for the device.

ORR was determined from the oil collected in the barrels on the auxiliary bridge and the oil collection time. The collection time was equal to the oil distribution time for the skimmer since there was characteristically, no oil build up in front of the skimmer during the tests.

$$\text{ORR} = \frac{\text{Oil Collected in Barrels}}{\text{Oil Distribution Time}}$$

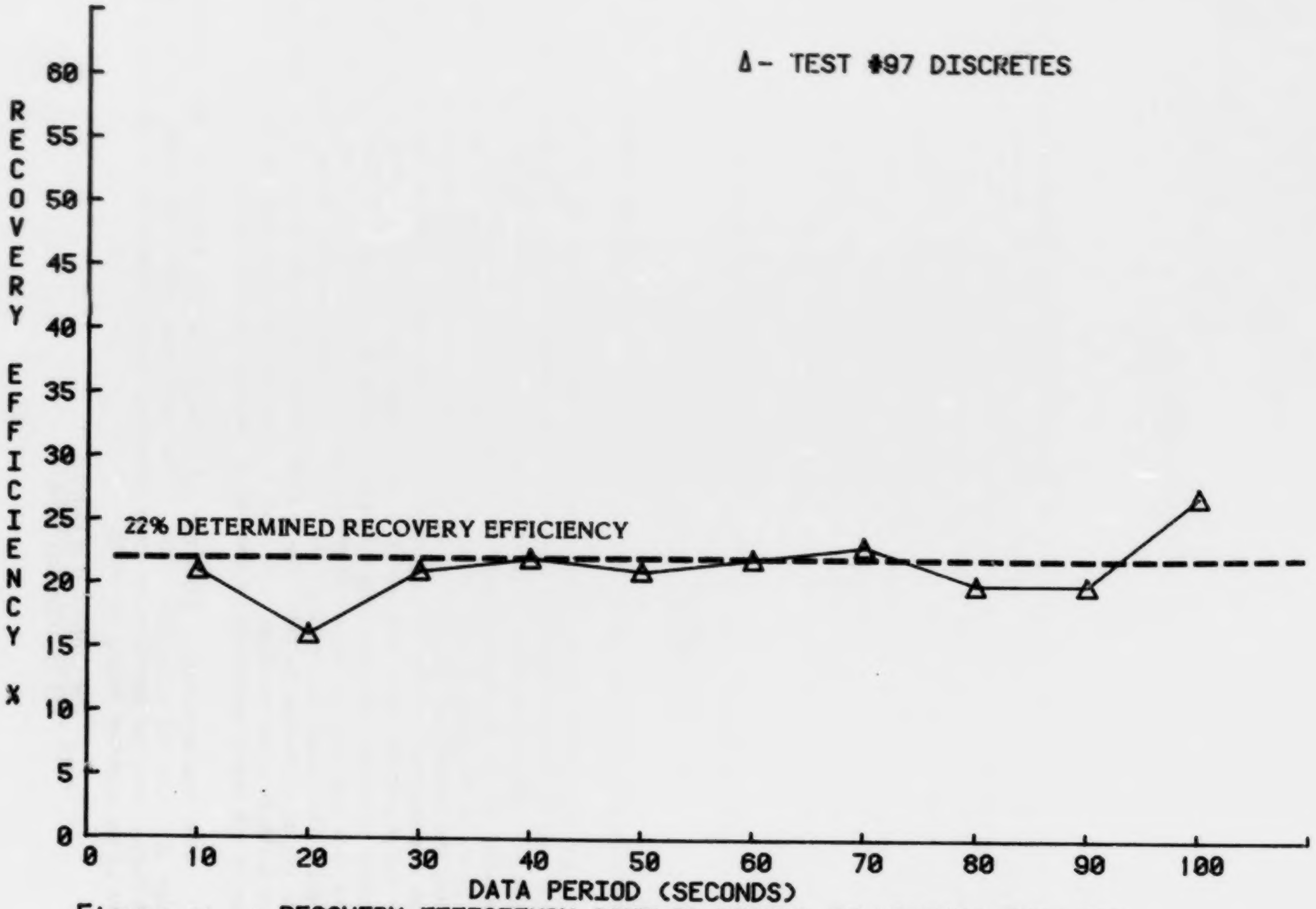


Figure 11 : RECOVERY EFFICIENCY SAMPLES VERSUS COLLECTION TIME FOR TEST 97. EXAMPLE OF A CONSISTENT RECOVERY EFFICIENCY.

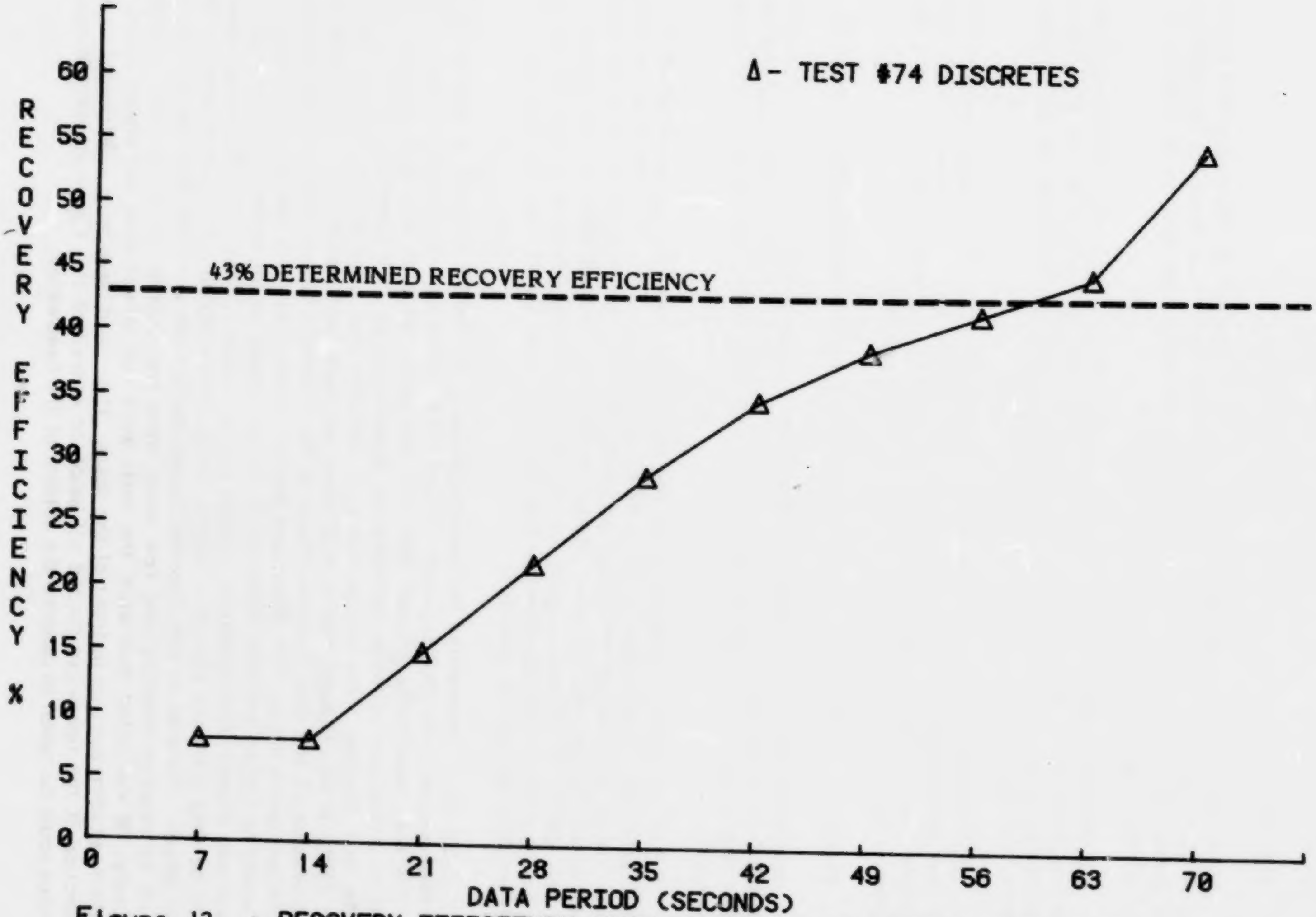


Figure 12 : RECOVERY EFFICIENCY SAMPLES VERSUS COLLECTION TIME FOR TEST 74. EXAMPLE OF AN INCREASING RECOVERY EFFICIENCY.

Many possible influences on TE, RE, and ORR were examined. They are listed here with their effects.

1. Tow Speed—

Maximum TE values in calm water were not affected by increasing tow speed (Figures 13, 14 and 15). Thus a high performance capability was shown to be available at all speeds up to 6 knots. Less than maximum TE values for medium oil (Figure 14) were included to give an indication of data scatter.

RE declined slightly as tow speed increased (Figure 16). This could have been caused by more water being washed onto the upper side of the belts by the slight bow waves produced by the hulls and belts. Less than maximum values of RE for medium oil were included to give an indication of data scatter.

ORR increased directly with tow speed (Figure 17). This could be expected since the percentage of oil recovered did not decline but the recovery time was decreased due to the higher tow speeds. Less than maximum values of ORR for medium oil were included to give an indication of data scatter.

2. Proximity of the belt speed to the vessel's forward speed (dependency on ZRV)--

Maximum TE values (Figure 18) point out that better performance is obtained when the belt is run about ½ to 1 knot faster than the vessel speed. The high result at -1 kt relative velocity is abnormally greater than the other two tests at the same parameters.

RE is not greatly affected until the belt speed exceeds the vessel speed by 1 knot (Figure 18). A reduction in RE is then very evident. This is a result of the belt pulling the oil slick across the water and exposing the belt to open water to the belt as belt speed further exceeds vessel speed. In the event the oil slick is thick enough, a fast belt speed will recover a good amount of oil and still maintain a high RE value. This was proven by test 169 when the belt was run 1 knot faster than the skimmer into a 10 mm slick (RE was 67 percent).

ORR results resembled the pattern produced by the TE results. A belt speed ½ to 1 knot greater than ZRV was best. A high ORR maximum appeared at -1 knot ZRV, but this was abnormally greater than the two other tests at the same parameters. Tests to investigate skimmer performance dependence on ZRV conducted at the onset of the test program were inconclusive. A decision was made to run the belts at -½ knot ZRV. It was thought that a belt speed one half knot slower than ZRV would be best because of the direction the fibers of the Astroturf leaned after passing through the rollers and wringer. The fibers are angled forward (towards the bow) and thus the oil would be forced into the Astroturf if the belt speed lagged behind the vessel speed. It was also thought that operating outside plus or minus 0.75 kt from ZRV would cause oil to be shed from the belt much like oil sheds from a towed containment boom at the same speed.[5] Because of the aforementioned, many tests were run with the belt speed at -½ kt relative velocity and few tests were run outside +½ or -½ knot relative velocity. It was noted that when the belts were run slower than the vessel speed a slight headwave built up in front of the belts. This could have been a detriment to oil collection if the headwave forced oil aside or entrained it. Close-up, slow motion movies could be taken to observe the actions of the headwave.

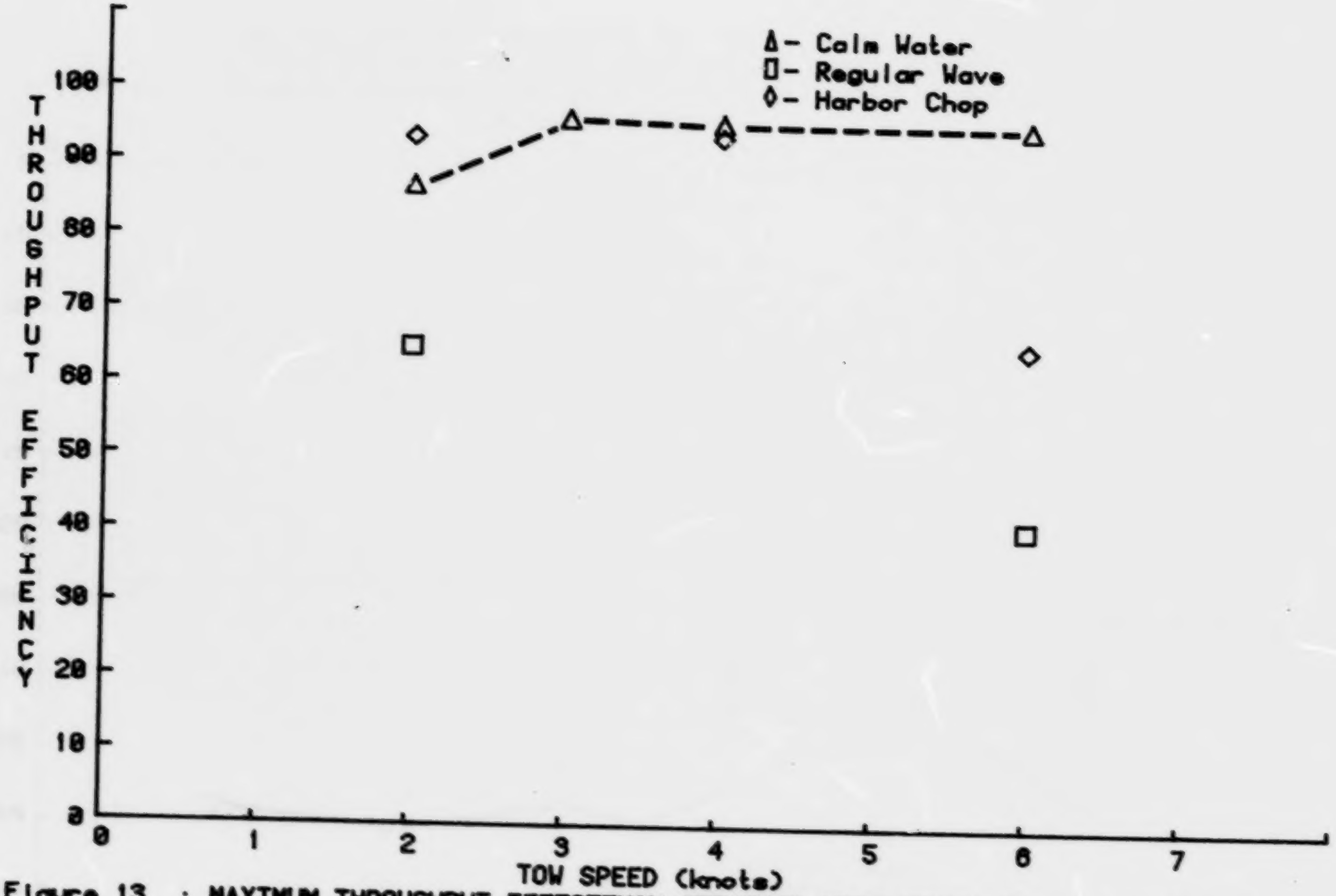


Figure 13 : MAXIMUM THROUGHPUT EFFICIENCY OBTAINED WITH HEAVY OIL - 3 mm SLICK, RUNNING THE BELT 1/2 KNOT SLOWER THAN VESSEL SPEED.

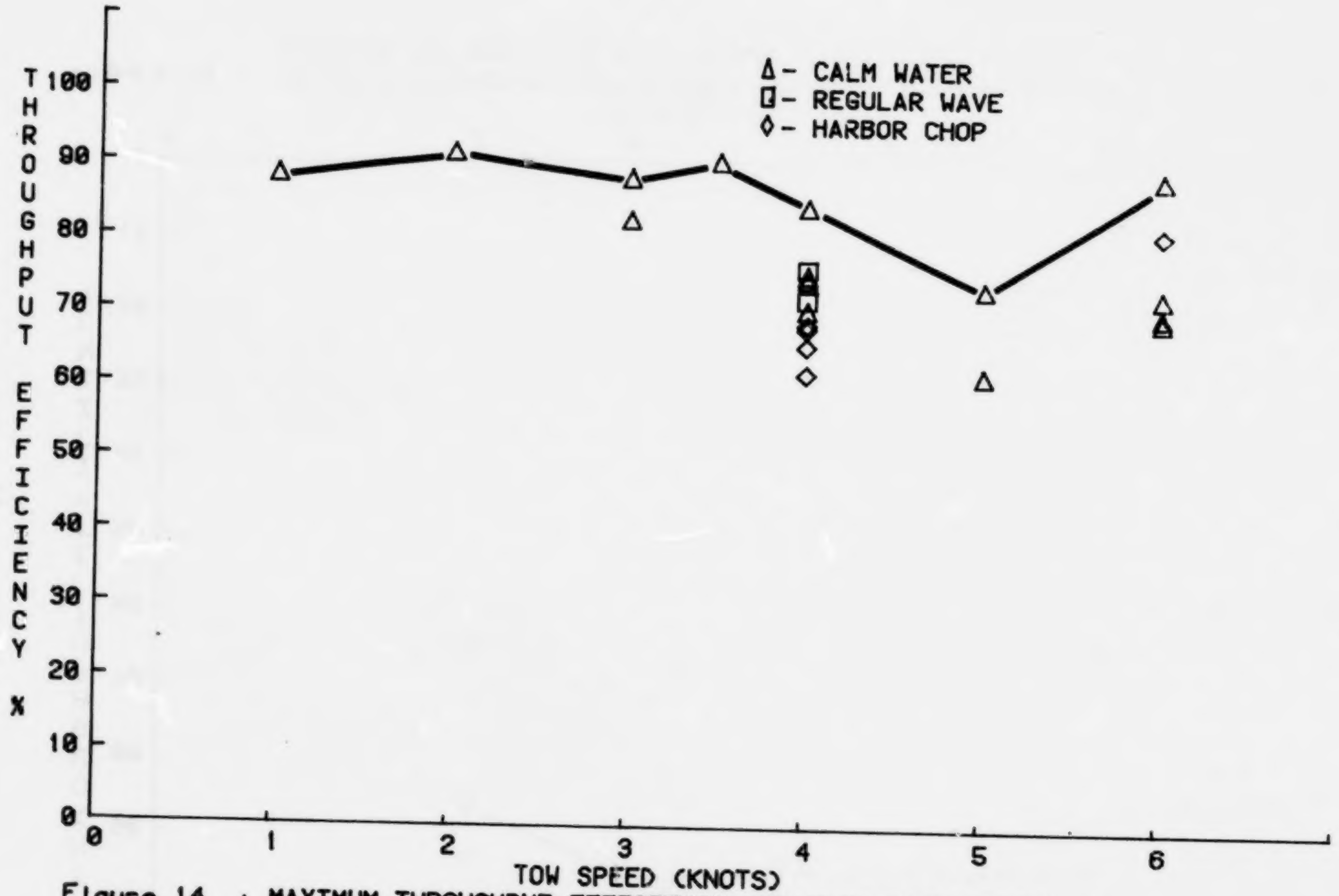
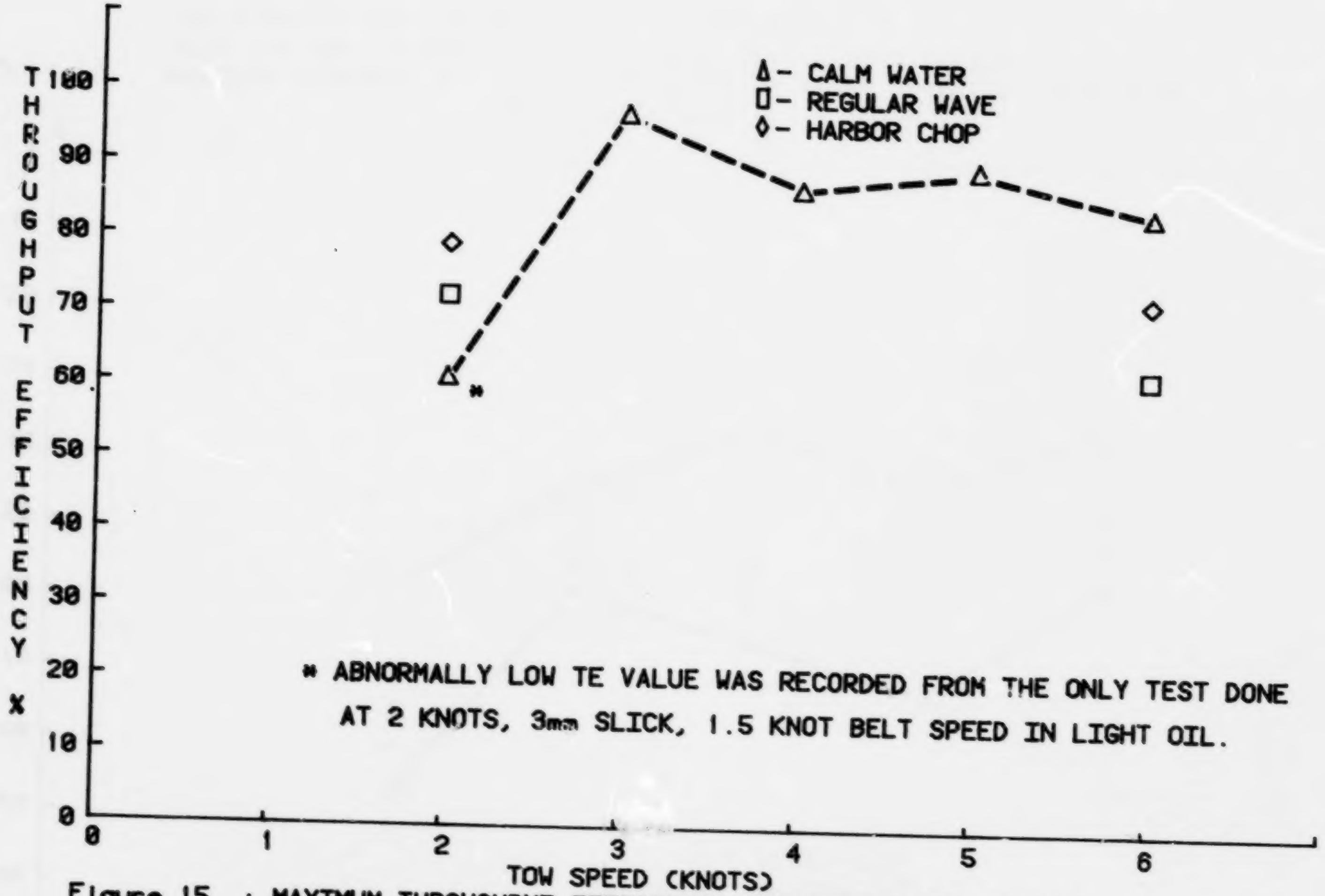


Figure 14 : MAXIMUM THROUGHPUT EFFICIENCY OBTAINED WITH MEDIUM OIL - 3 mm SLICK WITH BELT 1/2 KNOT SLOWER THAN VESSEL. THE SCATTER FOR THE MEDIUM OIL IS INCLUDED.



* ABNORMALLY LOW TE VALUE WAS RECORDED FROM THE ONLY TEST DONE AT 2 KNOTS, 3mm SLICK, 1.5 KNOT BELT SPEED IN LIGHT OIL.

Figure 15 : MAXIMUM THROUGHPUT EFFICIENCY OBTAINED WITH LIGHT OIL - A mm SLICK WITH BELT 1/2 KNOT SLOWER THAN VESSEL

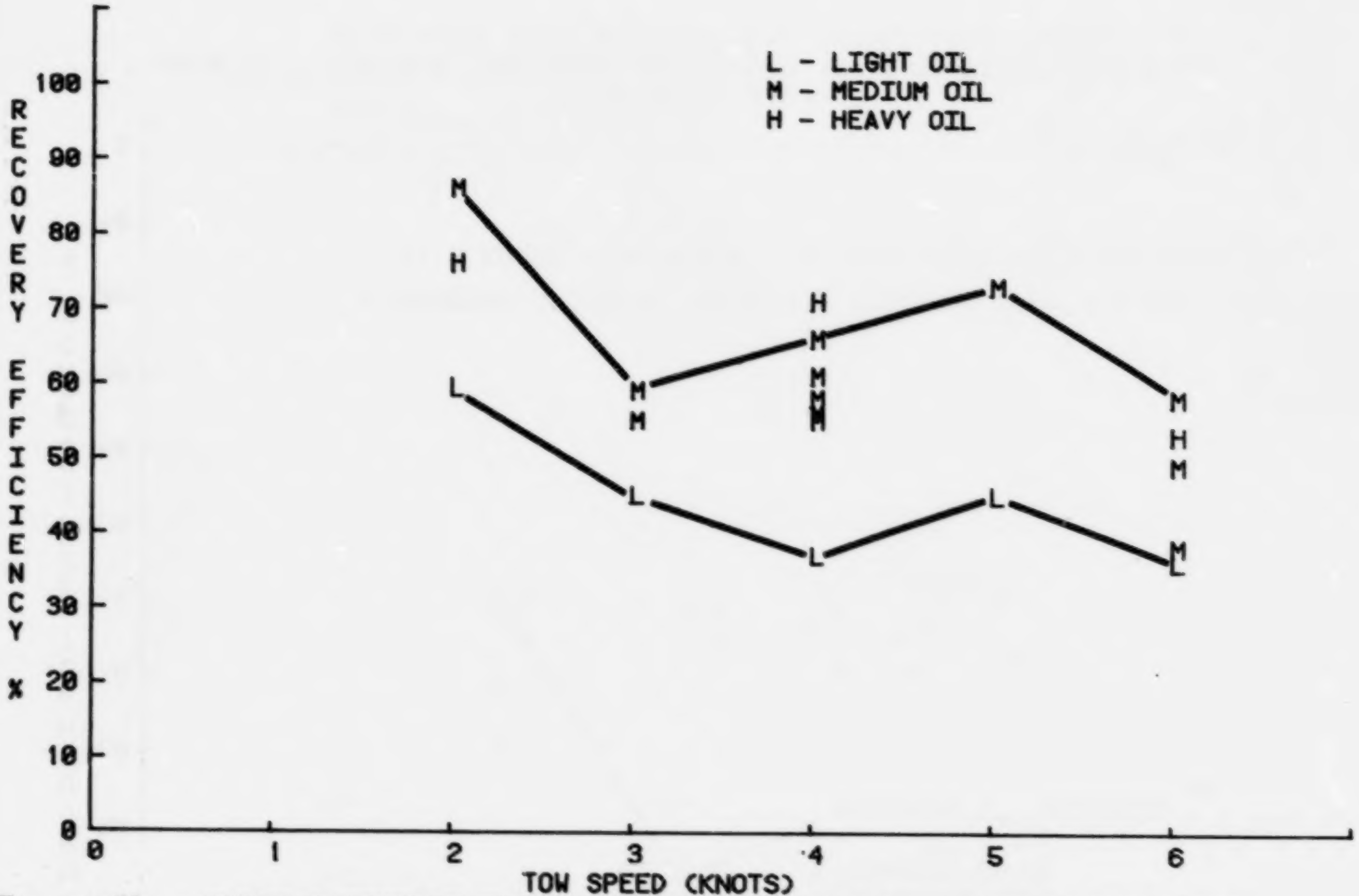


Figure 16 : MAXIMUM RECOVERY EFFICIENCY OBTAINED IN A 3mm SLICK IN CALM WATER WITH THE BELT SPEED 1/2 KNOT SLOWER THAN VESSEL SPEED. THE SCATTER FOR THE MEDIUM OIL IS INCLUDED.

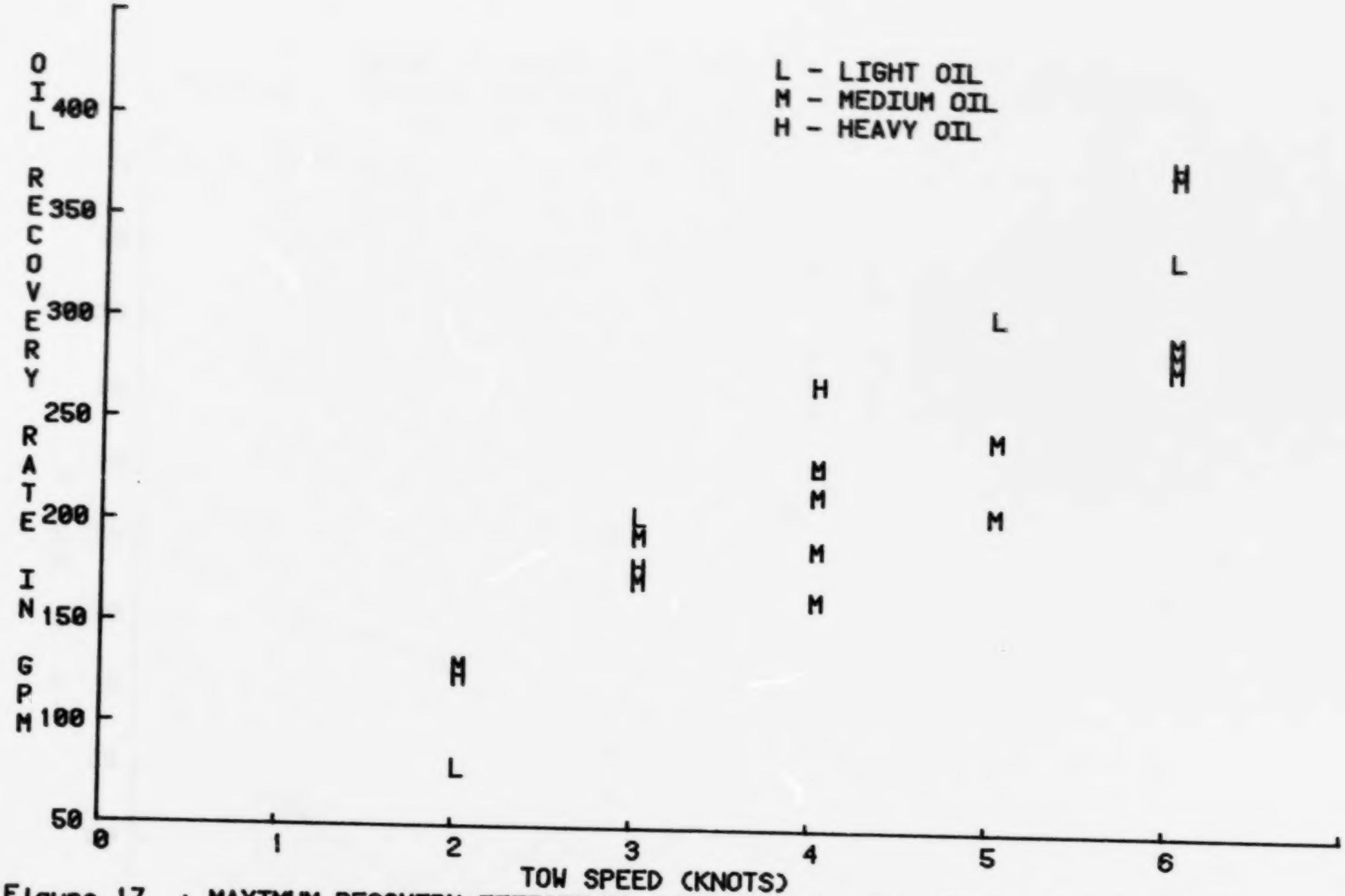


Figure 17 : MAXIMUM RECOVERY EFFICIENCY OBTAINED IN A 3mm SLICK IN CALM WATER WITH THE BELT SPEED 1/2 KNOT SLOWER THAN VESSEL SPEED.

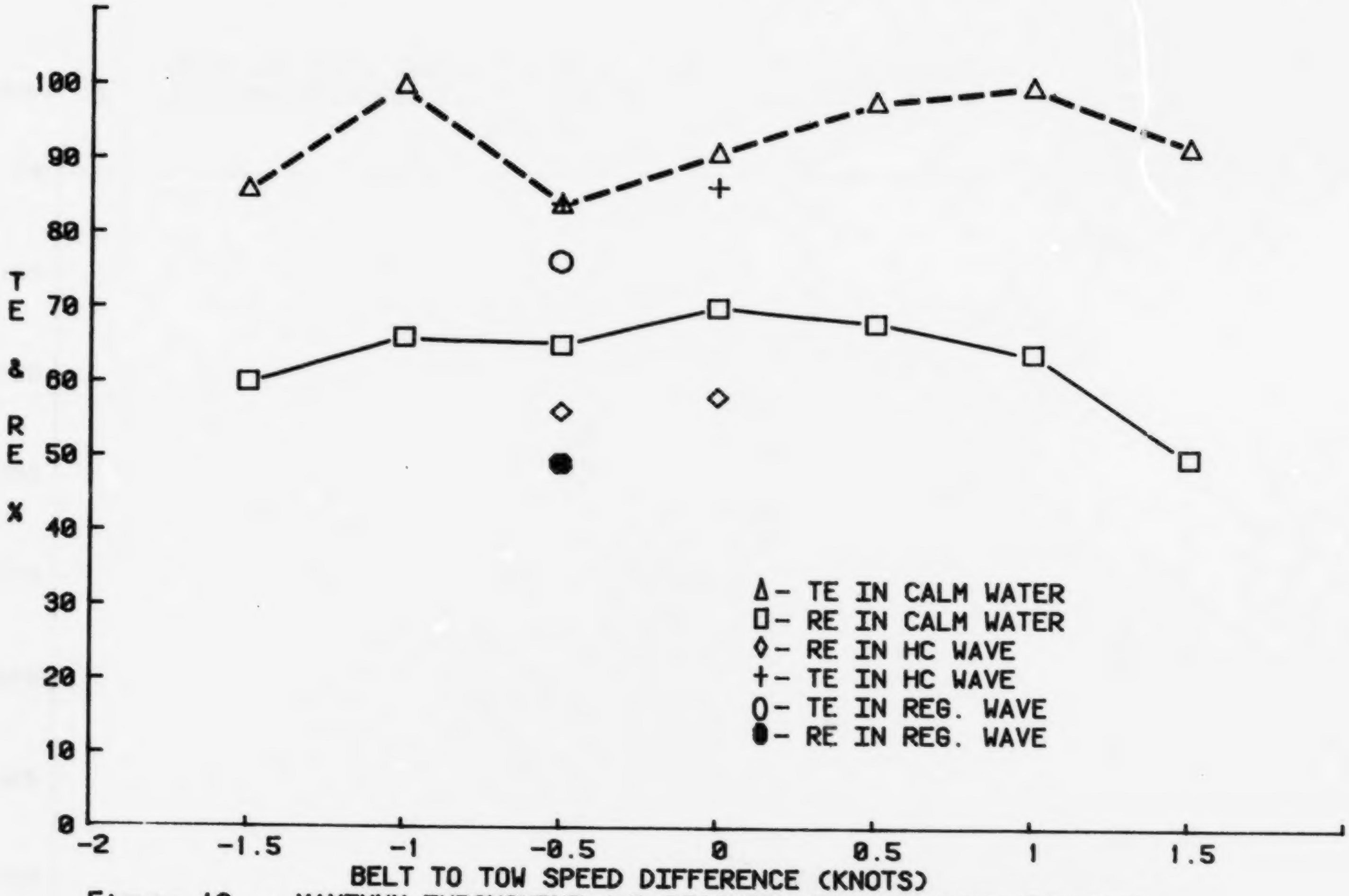


Figure 18 : MAXIMUM THROUGHPUT AND RECOVERY EFFICIENCIES OBTAINED USING DIFFERENT BELT SPEEDS AT 4 KNOTS IN MEDIUM OIL.

An attempt to film the action of the oil on the belt at belt speeds ranging from -1½ to +1½ kts relative velocity was inconclusive. A diver with a 16 mm underwater movie camera was towed beneath the skimmer at 2 kts while the belt speed was varied from ½ to 3½ kts. Interference with bubbles produced by the slick herding water jets and difficulties encountered holding the tow rope and the camera caused the film footage to be poor. However, it was noticed by the diver and could be seen somewhat on the film that there was never a great deal of oil loss from the belts at any point during the test run. The oil seemed to be protected from shedding by the belt fibers. Such a phenomenon was witnessed during a previous OHMSETT test when polyurethane foam cubes were placed in a containment boom and towed into an oil slick.[6] Much of the oil remained on the water, among the cubes. The cubes extended down into the water about ½ their total height and this was sufficient to protect the oil from the shearing action of the water passing beneath it.

3. Oil viscosity—

TE increased slightly with the heavier oils in 3 mm slicks (Figures 13, 14, and 15). In calm water, values of 85 to 95 percent were common over the range of test oils. In the 5 mm slicks (Figures 19 and 20) the belts appeared to have a greater sorption capacity for light oil.

RE also increased with the heavier oils (Figure 16). This is probably due to the heavier oils being retained in the fibers of the Astroturf and preventing water from reaching the felt and being sorbed with the oil.

ORR was not consistently affected by oil viscosity (Figure 17).

4. Waves—

TE, RE, and ORR declined when the skimmer was towed into waves with the worst performance occurring at the higher tow speeds and in regular waves. There were a number of causes for the decline, some of which could not be attributed to the design of the skimmer. The oil slick which was distributed to the skimmer was not as uniform as in calm water tests. The reason for this was the water surface following cloth on the oil distribution system which laid the oil onto the waves. In harbor chop (HC) or confused sea conditions the oil ran off the crests in the cloth into the troughs and then reached the water. The result was a non-uniform slick. The vessel was pulled through the waves from a fixed height 3 ft above the water's surface instead of propelling itself. This resulted in the vessel plowing into waves it might have rode over more smoothly. The attachment point on the main bridge was not arranged to tow the skimmer in the direction of the line force defined by the propulsion system. The point was lower than one in line with the normal direction of force. This caused the skimmer to squat during tow tests and thus the clearance between the waves and skimmer hardware was reduced. If an oil-carrying wave struck an object like the belt hold-down device, the oil slick was disturbed and some oil entrained into the water. When the device pitched, the catamaran hulls caused waves to surge between them, moving the oil slick to the centerline of the vessel. Vessel pitch was much more pronounced in regular waves than in harbor chop conditions. A thicker slick in the center of the vessel could over-saturate the inboard sections of the belts and some oil would not be sorbed. In addition, the skimmer was towed towards the tank wave generator, which simulated a head seas environment. According to the model tests conducted during the development phase of the skimmer, the vessel rode easier in

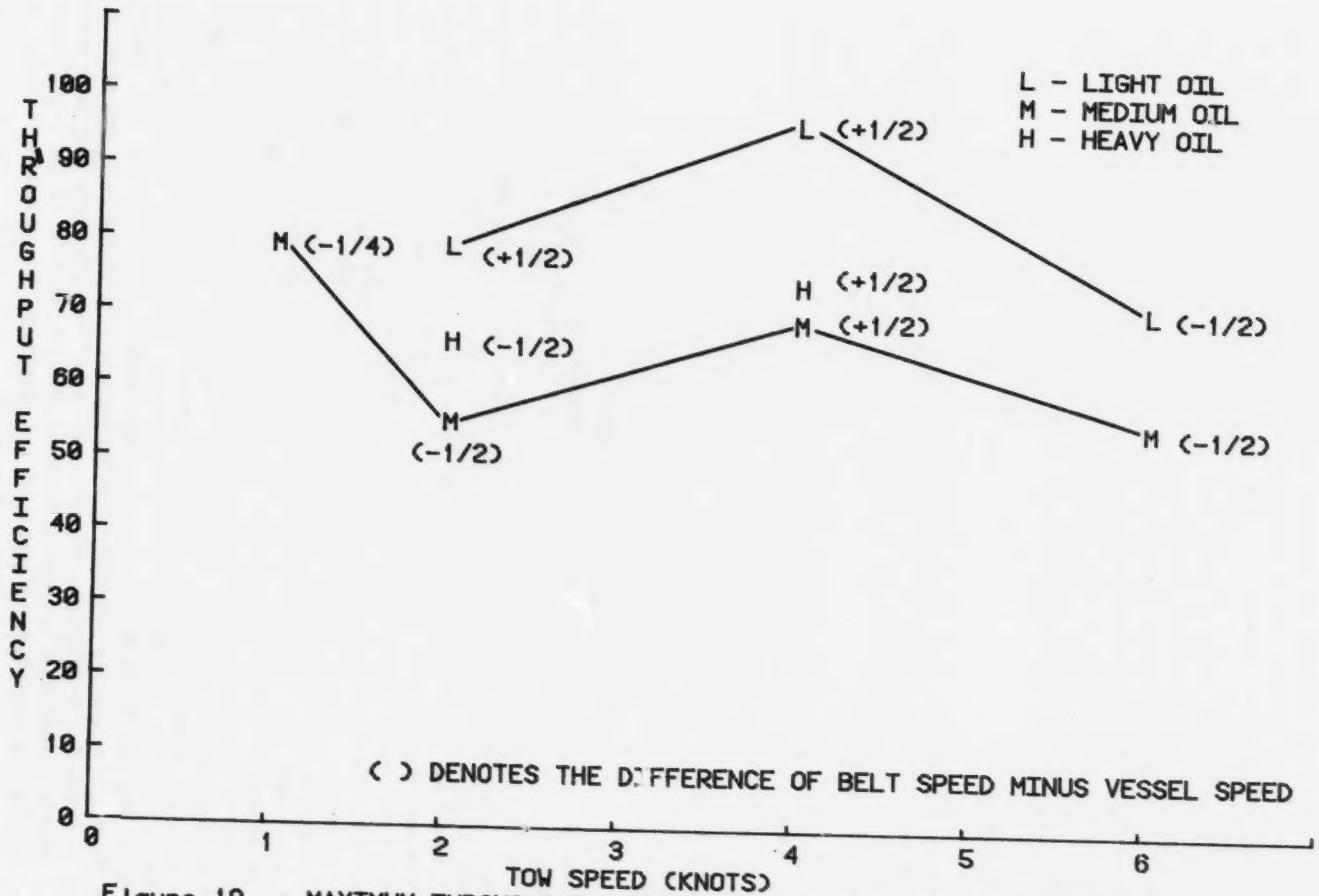


Figure 19 : MAXIMUM THROUGHPUT EFFICIENCY OBTAINED IN 5mm SLICK AND IN CALM WATER.

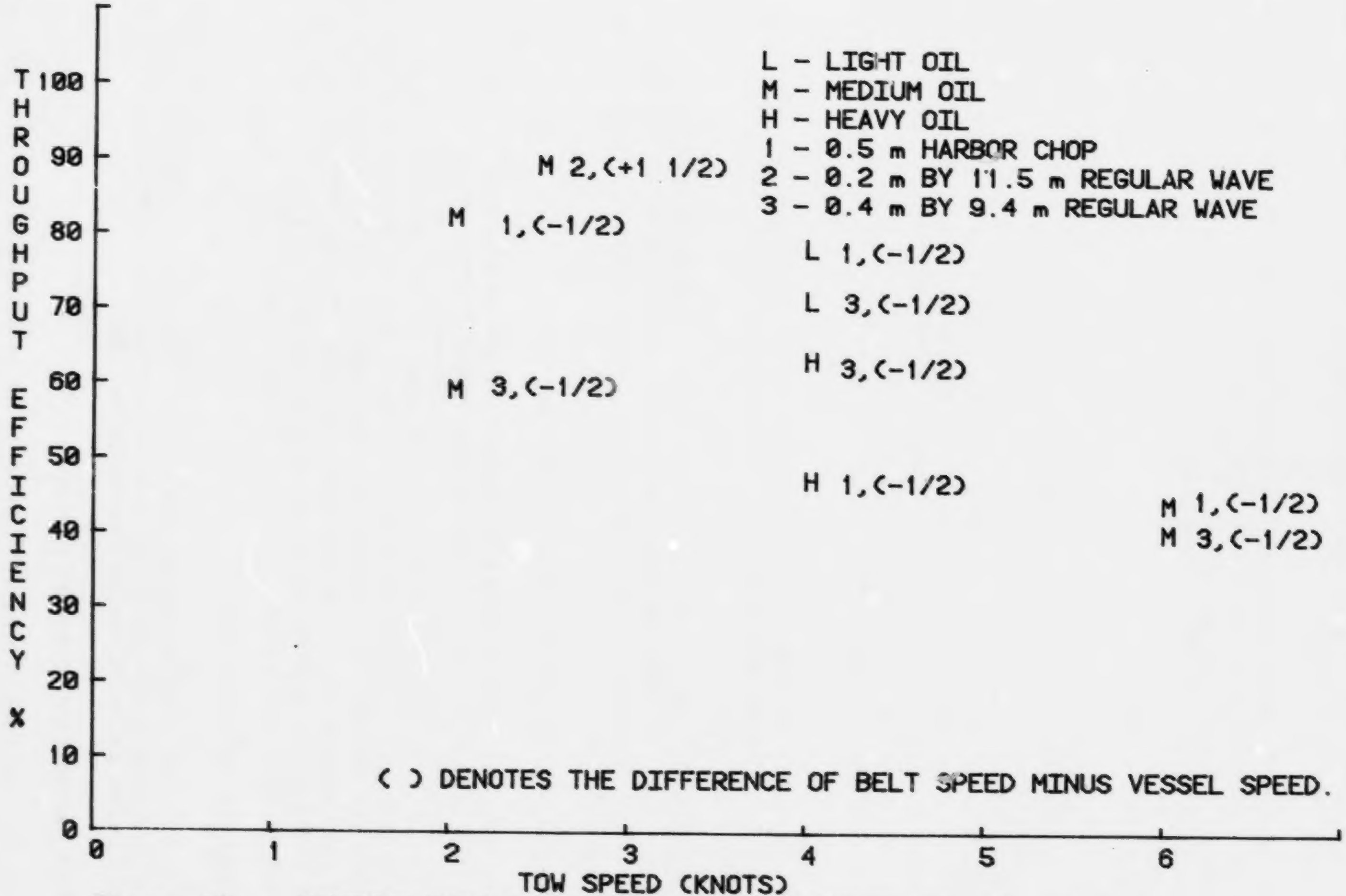


Figure 20 : MAXIMUM THROUGHPUT EFFICIENCY OBTAINED IN A 5mm SLICK AND IN WAVES.

following seas than in head seas. There was much less pitching and heaving[1]. Had the skimmer been towed following the waves at OHMSETT, the performance would have most probably been much better.

All of the oils tested had a low interfacial tension (IFT) in the vicinity of 2 to 10 dynes per centimeter. Normally, IFT would range from 25 to 30 dynes per cm. Oil forms droplets in water more easily if a low IFT exists. This would be a contributing, but not necessarily an overriding, factor in the poorer performance in waves.

5. Oil slick thickness--

TE performance fell off directly as slick thickness increased. Results of tests in 1-mm slicks often gave TE values greater than 100 percent. This was due to the wringer removing oil from the belt which had accumulated during previous tests or precharges. The 1 mm slick did not supply enough oil to prevent the oil from the felt inner lining between the Astroturf layers from being squeezed out. The TE in a 1-mm slick appeared to be about 95 to 97 percent TE judging from the small bit of oil left behind after a test. A 3 mm slick appeared to be optimum for adequate belt saturation and still maintaining a high TE (85 to 95 percent) while the 5 mm slick overloaded the belt and produced much lower values for TE (normally 55 to 80 percent).

RE generally increased with the thicker slicks, leveling off in the 40 to 60 percent range for slicks 3 mm or greater. Heavier oils produced higher RE results as the thickness increased.

ORR also increased with the thicker slicks and began leveling off in slicks thicker than 3 mm. An oil/water saturation limit is apparent in the oil recovery belts. This would point to running the belts faster than ZRV to apply more belt to the oil in order to sorb more oil.

6. Precharging the Astroturf belts prior to each test--

TE, RE, and ORR appeared unaffected by the precharge. It was seen in previous tests with a ZRV device[7] that running oleophilic fibers through water prior to an oil test stripped the fibers of the oil film necessary for optimum oil recovery performance. A precharge manifold was mounted on the forward section of the skimmer to deliver a small amount of oil to the belts prior to reaching test speed and the oil slick for the test. The performance was probably unaffected because the oil recovery belts were started up as the vessel tow was begun and brought up to speed with the vessel. That kept the belts operating at approximately a ZRV condition and eliminated the oil-stripping shearing action of the water against the belt.

7. Height of the rear drums--

TE, RE, and ORR appeared unaffected. The rear drums over which the astroturf belts entered the rear of the skimmer after sorbing oil were adjusted over a height of 9 inches during the test to investigate the effect.

8. Belt slackness (belt extender position)--

TE, RE, and ORR results were higher if the belts were slack. This parameter was not meant to be studied specifically when the test plan was formulated. The forward drive rollers were extended only far enough so that the belts would not strike the rear belt guide cross brace as they were drawn up from the water aft of the vessel. The results point to allowing the belt to conform as much as possible to the water's surface.

9. Air trapped beneath the belt due to wave action--

On wave tests where the vessel pitched a good deal it was feared that air would be trapped under the belt as it was laid down on a wave trough and prevent oil from reaching the belt. To examine the reaction a pocket of air had on the belt, a SCUBA diver released air up under the belts and watched the results. At first, it appeared the air passed up through the belts since breath after breath of air bubbles rose to the belt and disappeared over an area of about 2 ft^2. Finally, an air pocket was formed and the belt was raised above the water. It is estimated that about 6 breaths or about 0.1 ft^3 of air was required to form the air pocket. From this experiment there appears to be sufficient openings in the belt for the little bit of air which could be trapped beneath the belt in waves and the oil it contacts. In addition, from observations during the test when the belt was laid on the oil flat (instead of being rolled on top) during wave tests, it appeared to blot the oil very quickly. This was seen when the vessel pitched back and lifted some of the belt back off the water.

Mechanical

The installation, operation and performance of the various mechanical portions of the skimmer were examined during the test program. Those listed in the following portion of the report were considered to have a major influence on the device.

1. Belt hold-down device--

This item fulfilled its design function of maintaining a semi-taut belt and an early belt-to-slick contact point. However, during wave tests and high speed calm water tests, the lower portion of the device struck the water, entrained the oil slick and sent a breaking wave forward into the yet unreached oil slick. During most of the wave tests it was tied back to avoid disturbing the oil slick. The need for having a system which guides the belt to an early slick contact is questionable if the belt is run faster than the vessel speed (better performance condition). In such a case the belt would drape almost straight down from the forward rollers and thus make early contact with the slick.

2. Rear belt guides--

In order to keep the oil recovery belts from mistracking and riding off of the rear rollers, vertical plate belt guides were extended aft between the rollers and on the outboard edges of the rollers. An above-water cross brace tied the plates together. The belt guides worked well but the cross brace was situated too close to the rear drums. If the oil recovery belts were too slack, they would trail the rear drums slightly and be lifted off of them during a rearward pitch of the vessel. In such cases the belts would often rub against the cross brace (Figure 1) and lose the oil they sorbed. If the belt guides were extended further aft, the belts could periodically lift from the rear drums due to slackness and not strike the cross brace.

3. Oil recovery belt performance--

The belts proved very durable and reliable throughout the tests. Slight tearing of the alligator lacing connections was the only easily visible sign of wear. Both belts stretched about one percent over the test program. The elongation of the belts did not cause any noticable degradation of performance or any mechanical problems. The starboard belt measured about 6 in longer than the port belt throughout the test program. This was a slight problem in that the starboard belt would be slacker and contact the rear belt guides cross brace sooner than the port belt. When this occurred the forward rollers were extended a bit to further tension both belts.

4. Neoprene squeeze belt--

The neoprene belts also proved durable and reliable throughout the program. It was discovered that the starboard neoprene belt did not meet the thickness specification. This could account for the occasional appearance of one oil recovery belt not being wrung as dry as the other. Grab samples of collected fluid were taken from points within the wringer system to try to investigate this theory, but due to the uneven distribution of oil on the belts the oil/water composition of the samples rendered inconclusive results.

5. Wringer/drive assembly--

This portion of the device functioned very well throughout the test program. It brought the belts up to speed evenly and quickly at the start of a tow test. This was the predominant area of concern for testing. Otherwise, the belts would have had to have been started before the tow test was begun. This may have stripped the necessary oil precoat from the fibers and thus diminished the oil retention ability of the belts for the test run.

Fluid was wrung from the belts with a minimal amount of splashing as they passed through the wringer. The fluid flowed readily to the collection trough where it was pumped to the barrels on the auxiliary bridge.

6. Scrapers--

A good amount of fluid was removed from the belt by the scrapers. Samples grabbed from the scrapers during medium oil tests proved to contain a significantly greater amount of oil than the determined RE of the test. The percent oil in the grab samples varied from being equal to the RE to being twice as much. This means scrapers could be given priority over a wringer/drive mechanism for removing oil. If it is found that most of the oil clings to the outer, Astroturf layer of the belt, it may be possible to eliminate the inner felt layer and use only one layer of Astroturf. This would significantly reduce the cost of the belts.

Areas where unwanted fluid loss from the belt occurred were few and were dealt with. A roller over which the belt passed and subsequently dripped oil onto the wrung portion of the belt below was removed. The rear belt guide cross brace was avoided by maintaining proper tension on the belts. The forward rollers which caused significant fluid to be squeezed from the belt caused a problem because the fluid fell upon and disturbed the oil slick to be encountered. This was remedied by placing a trough beneath the rollers and across the front of the skimmer. The fluid which entered the trough was diverted out to the sides and into the tank water.

Comparison of Skimmer Performance with 1977 Test Results

In the summer of 1977, a machinery mock-up of the sorbent belt wringer/drive system was built by Shell Development Co. and tested at OHMSETT.[1] A direct comparison of the mock-up to the ZRV skimmer would not be useful because of the many differences between them. The machinery mock-up was housed in a framework supported between the main and auxiliary bridges (Figures 21 and 22). The only part of the system to contact the water was the sorbent belt. Waves effected no motion of the system other than flexing the belt. In contrast the ZRV skimmer reacted to waves and penetrated the water surface with the catamaran hulls on either side of the sorbent belts. The mock-up's oil sweep width was equal to the width of the belt, 2 feet. The oil sweep width of the ZRV skimmer was the inside distance between the catamaran hulls, 9 feet, while the belts were only a total of 7 feet wide. This left 22% of the inlet width not covered by sorbent belt. Oil laying in this non-covered area was moved towards the belts by small water jets located at the bow of the skimmer. These jets were not always 100% effective and when they were the oil slick encountered by the edges of the belts was appreciably thickened. The chance of over saturation of the edges of the belts was thus increased.

The percentage of the oil encountered by the mock-up system was estimated by observers. Such estimates had values ranging from 55 to 100%. The inaccuracy of the estimates often resulted in TE values greater than 100%. The oil encounter percentage for the ZRV skimmer ranged from 95 to 100%. The room for errors in encounter percentages with the mock-up was much greater.

The turf material which composed the outer layer of the sorbent belts was of slightly different construction on the skimmer than on the mock-up. The effect of the change is unknown.

TE results of the ZRV skimmer in calm water were well above 78% of the TE results of the mock-up in calm water (Figure 23) skimmer RE was greater than 0.78 mock-up RE. This suggests the skimmer's belt and machinery worked at least as well as the mock-up in calm water since the belts only covered 78% of the skimmer's entrance width. The skimmer generally outperformed the mock-up in harbor chop, although the mock-up's maximum exceeded that of the skimmer. The skimmer did less well in regular waves. Motion of the skimmer in harbor chop was not much different from that in calm water and the hulls protected the belts from cross-tank waves which could disturb the belt-to-slick contact and wash water onto the belt. However, in regular waves vessel response to waves was pronounced. The hulls surging through the head seas created bow waves which washed the oil in towards the center of the device which oversaturated some of the belts. The waves could have also entrained oil into the water beyond the reach of the belts.

RE values of the mock-up and skimmer were comparable at tow speeds below six knots (Figure 24). At six knots, the mock-up outperformed the skimmer. Since hydrodynamic energy of a moving fluid is directly proportional to the velocity squared, it is possible that anomalies in the system could show up at six knots which were not evident below that speed. Also the hydraulic system of the skimmer was not sufficiently powered to drive the offloading pumps and the belts at the desired speed at six knots. The result could have been a slight loss of squeezing efficiency.

The RE results in waves are similar to the TE results. The skimmer outperformed the mock-up in harbor chop but did less well in regular waves. The pitching of the vessel in regular waves caused less oil to be sorbed by the belts and so more water could be taken up. In harbor chop the hulls prevented water from washing onto the top of the belts and thus driving down the RE.

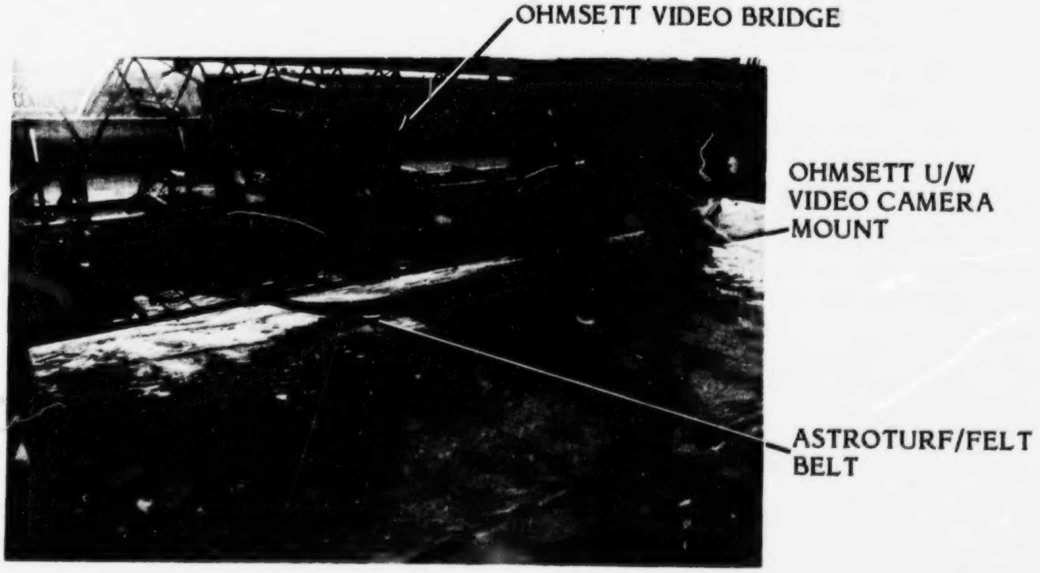

OHMSETT VIDEO BRIDGE
OHMSETT U/W VIDEO CAMERA MOUNT
ASTROTURF/FELT BELT

FIGURE 21. SHELL MOCK-UP OF ZRV OIL RECOVERY SYSTEM AT OHMSETT (WEST SIDE VIEW).

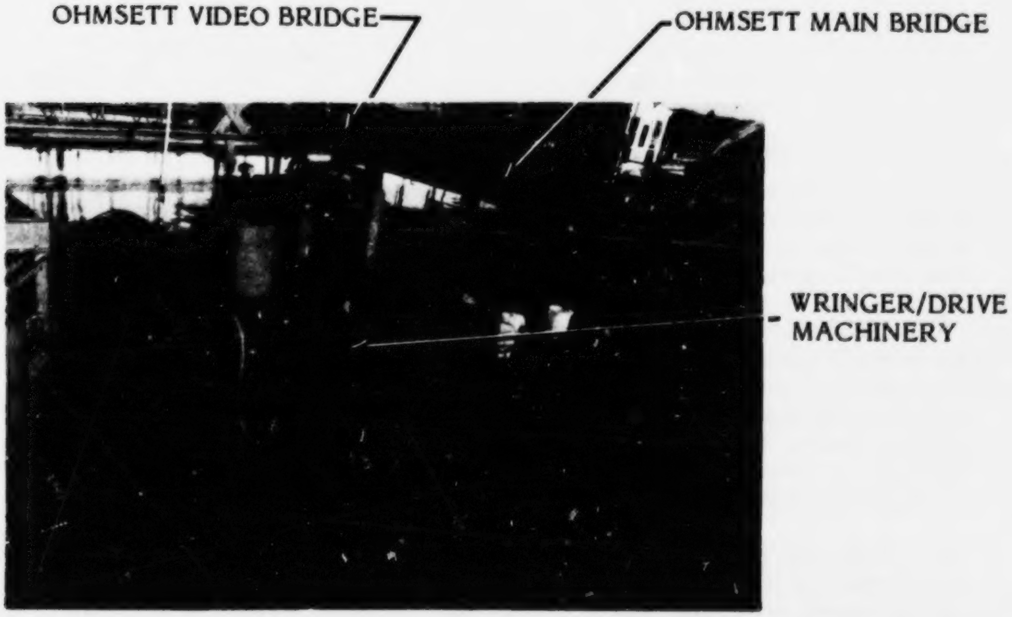

OHMSETT VIDEO BRIDGE
OHMSETT MAIN BRIDGE
WRINGER/DRIVE MACHINERY

FIGURE 22. SHELL MOCK-UP OF ZRV OIL RECOVERY SYSTEM AT OHMSETT (EAST SIDE VIEW).

The ZRV skimmer should have had a slightly higher RE than the mock-up in calm water if the entire 9 foot wide oil slick was directed to the two 3.5-foot wide belts. The proximity of the results suggest the wringer and scrapers of the skimmer squeezed a greater percentage of fluid from the belts with water being the dominant fluid in the belt. The different construction of the turf material could have resulted in a greater percentage of water pick up.

When calculated in gpm per foot of belt width, the ORR of the two systems is generally comparable at tow speeds below 6 kts (Figure 25). At six knots the mock-up outperformed the skimmer in calm water and regular waves. The skimmer excelled in harbor chop conditions at all speeds.

Since the skimmer received a swath of oil 22 percent wider than the belt coverage, one would expect the skimmer to excel in ORR as a system. The non-fulfillment of this expectation could lie in the kind of oil slick the mock-up encountered. An average slick thickness was calculated depending upon how wide the known quantity of oil distributed spread before it reached the belt. This would have been accurate if the oil slick spread evenly. But by the nature of the spreading process, the oil slick would be thicker in the center of the slick until equilibrium is reached. It is quite likely that the center of the slick which the mock-up encountered was thicker than the calculated average. Thus a greater amount of oil was available to the belt for recovery.

Based upon the 1976 results of the machinery mock-up, performance projections of the full-scale skimmer were made (Table 2). The ZRV skimmer met or surpassed almost every oil recovery performance projection in the OHMSETT tests.

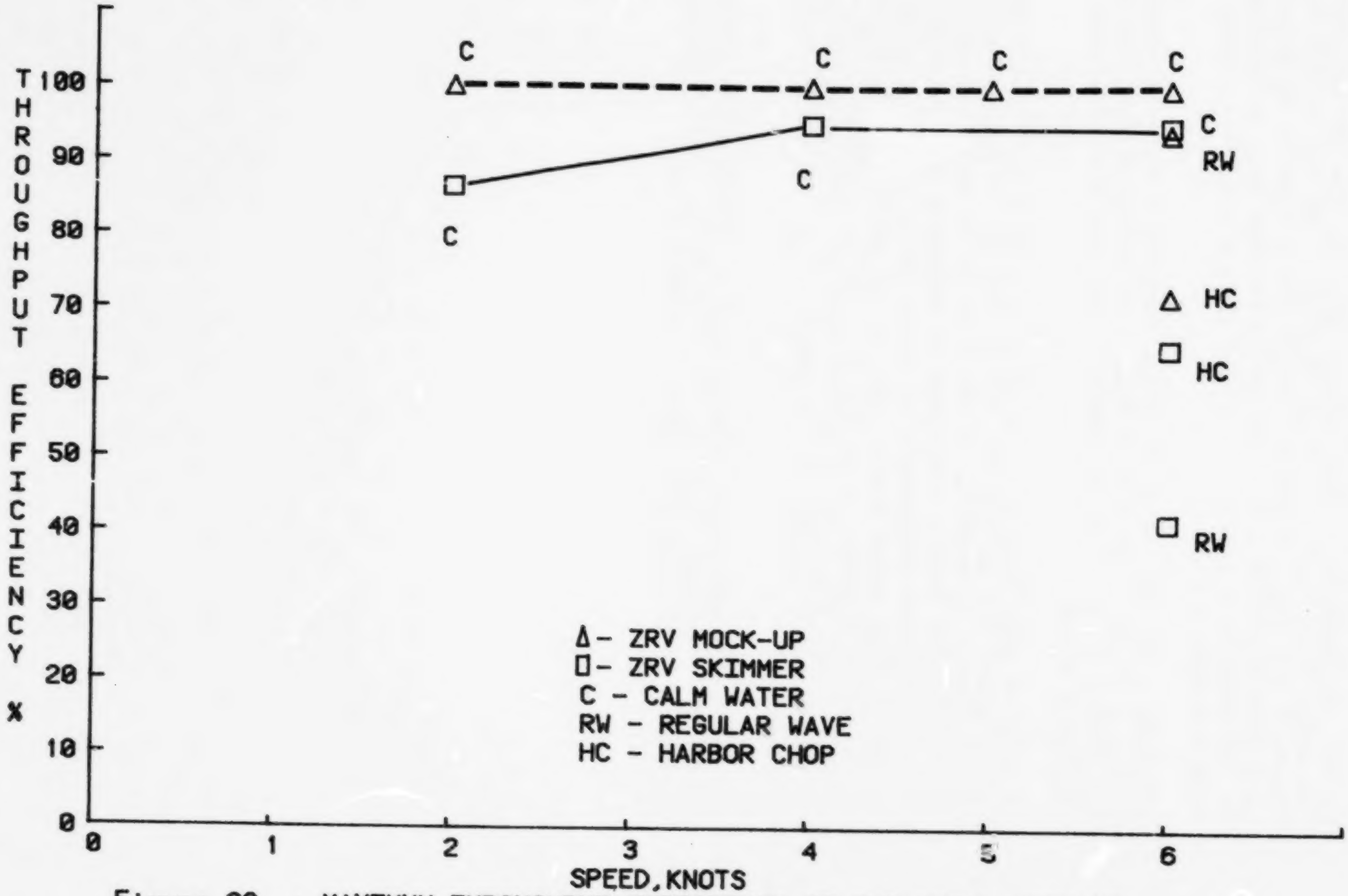


Figure 23 : MAXIMUM THROUGHPUT EFFICIENCY OF THE SHELL MOCK-UP AND THE ZRV SKIMMER IN HEAVY OIL.

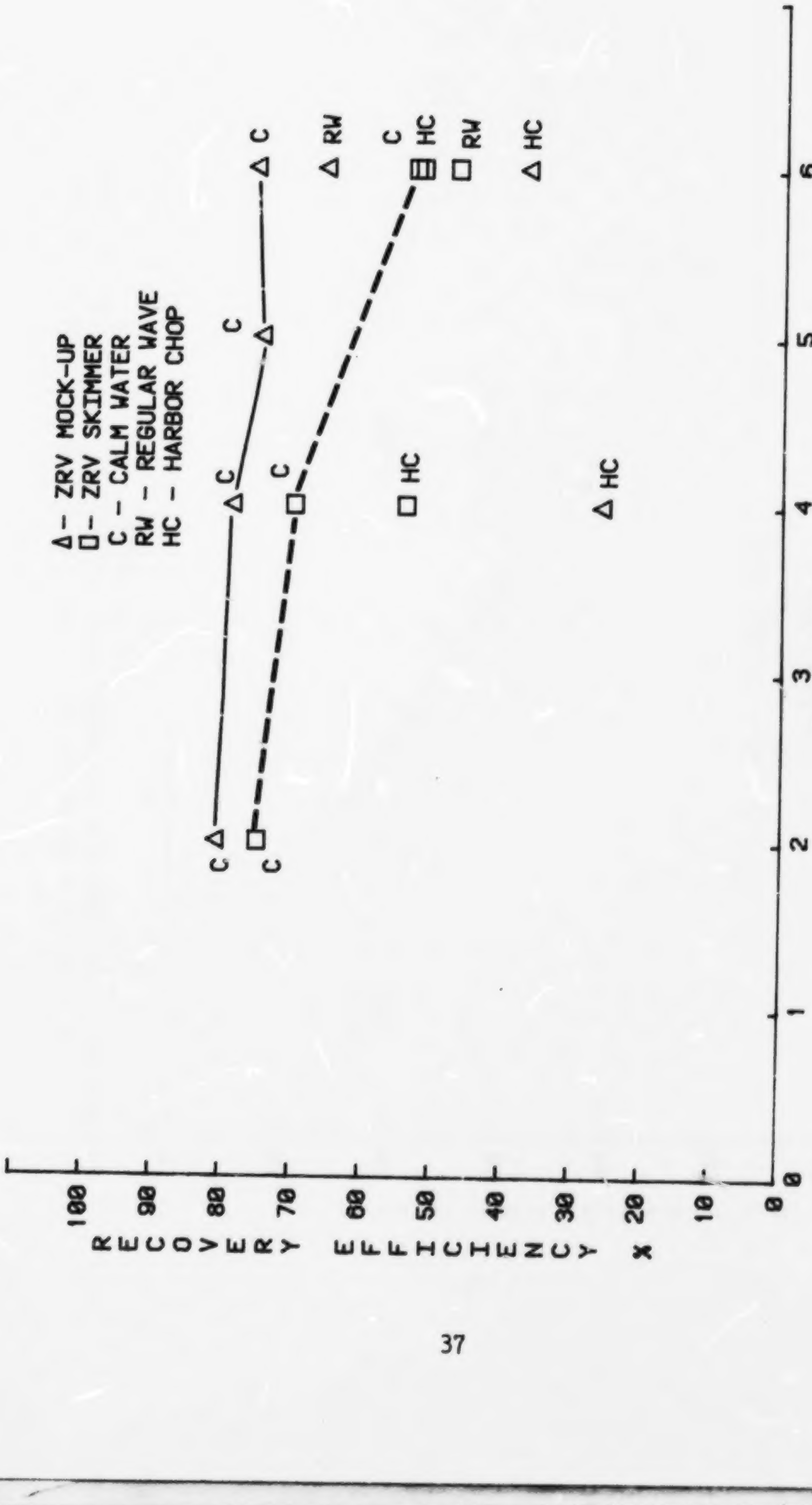


Figure 24 : MAXIMUM RECOVERY EFFICIENCY OF THE SHELL MOCK-UP AND THE ZRV SKIMMER IN HEAVY OIL.

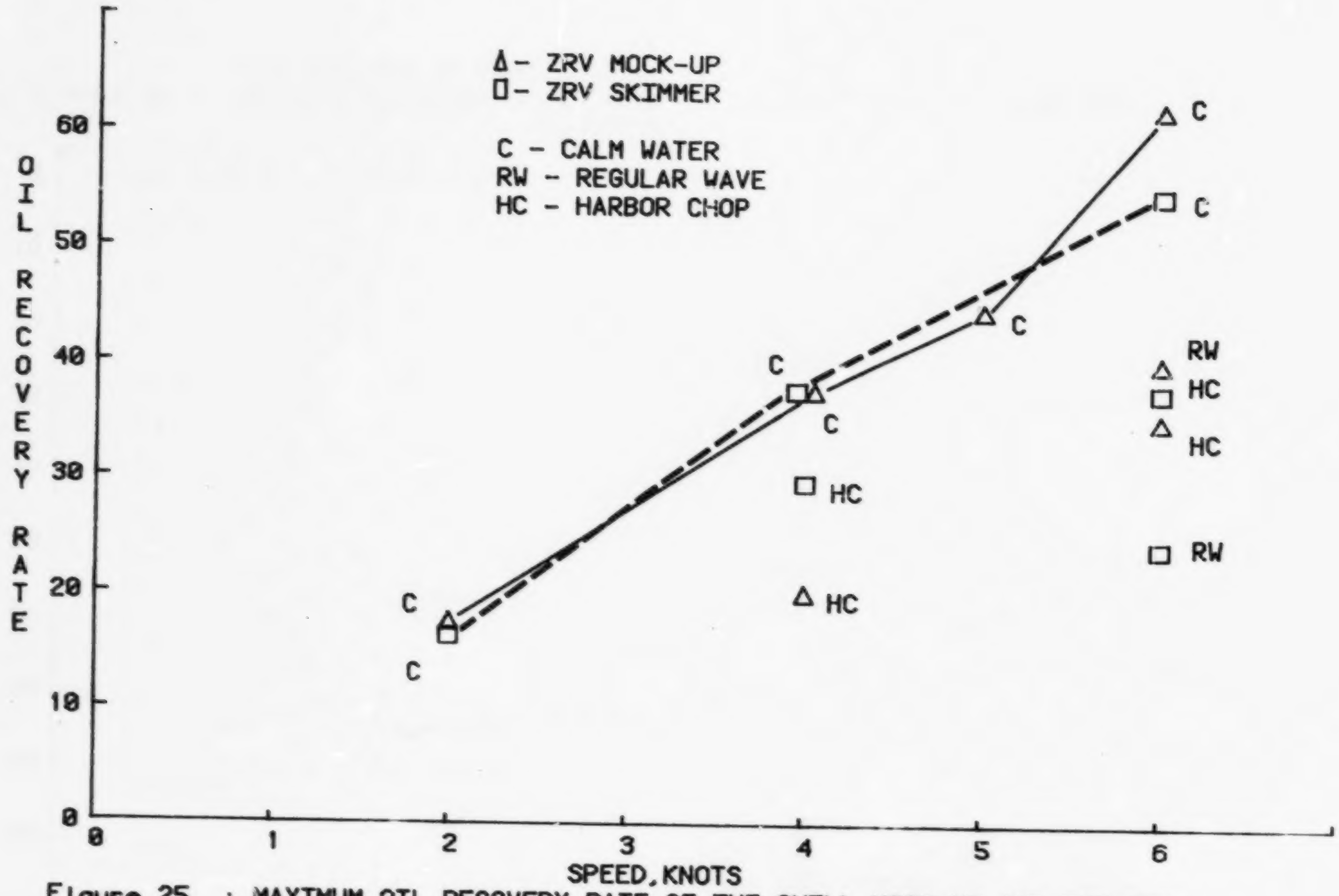


Figure 25 : MAXIMUM OIL RECOVERY RATE OF THE SHELL MOCK-UP AND THE ZRV SKIMMER IN HEAVY OIL. (ORR IS IN GAL/MIN PER FT OF BELT WIDTH)

TABLE 2. ZRV SKIMMER PROTOTYPE PROJECTED PERFORMANCE

	Condition	Capability
1.	Seagoing Ability - Waves - Current	
a)	Survival	a) 10 knot current with 4-foot waves and 20 knot winds
		b) 6-foot wave height with 40 knot wind for one week
b)	Skimming	10 knots current with 2-foot confused seas
2.	Speed and Maneuverability	
a)	Transit	10 knots
b)	Skimming	8 knots - Towing 14,000 gal. Storage bag
		6 knots - Towing 95,000 gal. Storage bag
3.	Oil Recovery	
a)	Viscosity range	2 - 2000 cSt
b)	Recovery Rates	
i)	Current or calm water 3 mm slick	278 - 315 gpm @ 6 kts
ii)	Two-foot irregular waves 3 mm slick	236 - 270 gpm @ 6 kts
iii)	Current or calm water 10 mm slick	500 - 600 gpm @ 6 kts
c)	Recovery Efficiencies	
i)	Current or calm water 3 mm slick	35-45% @ 6 kts, 2-30 cSt oils 60-75%@6kts,100-1200 cSt oils
ii)	Two-foot irregular waves 3 mm slick	25-35% @ 6 kts, 2-30 cSt oils 40-55%@6kts,100-1200 cSt oils
iii)	Current or calm water 10 mm slick	80-95% @ 6 kts, 2-1200 cSt oils

(Continued)

TABLE 2. (Continued)

Condition			Capability
	d)	Throughput Efficiencies	
	i)	Current of calm water 3 mm slick	90-100% @ 6 kts
	ii)	Two-foot irregular waves 3 mm slick	90-100% @ 6 kts
4.	Belt Life		Over 200 hrs

CONCLUSIONS

The USCG ZRV proved itself able to continuously recover and offload a substantial amount of oil in every wave condition (calm water to a 2.25 ft harbor chop) and at every tow speed (1 to 6 knots) produced at OHMSETT during this test program. The type of oil (heavy, medium and light) and oil slick thickness affected performance with heavy oil and a thick slick being the most difficult to recover. The maximum performance of the device recovering a 3-mm oil slick is shown in Table 3.

TABLE 3. MAXIMUM PERFORMANCE (3 mm OIL SLICK) FOR ALL OILS

	2 knots			4 knots			6 knots		
	TE (%)	RE (%)	ORR (gpm)	TE (%)	RE (%)	ORR (gpm)	TE (%)	RE (%)	ORR (gpm)
Calm	92	85	123	100	70	278	95	64	384
1.6' HC	93	51	126	94	54	242	81	56	326
2.3' HC	N/A	N/A	N/A	72	60	191	N/A	N/A	N/A
1.2'x31' wave	72	41	96	76	48	199	62	47	243

The maximum ORR was 471 gpm (Test No. 152) RE = 54%, TE = 53%; the slick thickness was 10.4 mm.

The tests were determined to be reliable indicators of device performance based upon a Box Behnken analysis of the data performed by the U.S. Coast Guard (Appendix E).

At OHMSETT, the skimmer was assembled easily within a few hours using a 70-ton crane and three men. The lifting apparatus which accompanies the skimmer greatly assists assembly and lifting the entire device. Assembly could have been accomplished much faster if an experienced crew were employed.

There were very few problems with the machinery or drive engines. The prototype system is, however, slightly underpowered since the fire pumps, offloading pumps and belt drives cannot be used to their maximums simultaneously.

Waves decrease performance due to vessel motion and rolling waves produced from wave-to-vessel contact.

The skimmer obtained better results in heavier oils in 3 mm slicks but in 5 mm slicks a greater amount of light oil was sorbed by the belts.

The device appeared to perform better when the belts were run slack. The best belt speed was about 0.5 to 1.0 knot faster than ZRV.

The precharging of the belts prior to an oil test did not appreciably affect device performance.

The lowering of the rear drums did not have an effect on device performance. This also indicates that slight variations in trim of the vessel would not adversely affect performance.

The belt hold-down device contacted the oil slick and entrained oil beyond the reach of the belts during wave tests and six knot calm water tests.

Fluid which was scraped from the belt contained a greater percentage of oil than the overall RE of the test. The scrapers appeared to remove much of the oil from the belt while the wringer appeared to remove much of the water.

Bars, braces and rollers which contacted the oil-laden composite belts stripped oil and water from them. This could dump recovered oil back on the water or onto a recently wrung portion of the belt and thus affect oil recovery performance.

A hydrocarbon sniffer test indicated there was no explosive vapor concentrations in the oil skimmer under the test conditions (Appendix G).

Of the two oil herding devices tested, the water jet outperformed the air jet boom at every tow speed and could also perform in wave conditions while the air jet boom, as tested, was limited to calm water (Appendix H).

Wave response tests indicated the vessel to be sea kindly and a stable craft (Appendix I).

RECOMMENDATIONS

The consistent performance of the device over the spectrum of tow speeds and wave conditions proved the viability of the concept and design. Study and development of the oil skimmer should continue with efforts to economize and optimize the vessel.

Unless a redesign of the front drive roller system is undertaken, an oil drip trough should be mounted beneath and in front of the forward rollers to divert any oil and water which is squeezed from the belt as it passes through these rollers. Unchecked, such oil and water would fall directly on the oil slick in front of the contact region of the belts. This would disturb the slick and entrain oil below the water's surface where the belts cannot recover oil.

Three vertically directed water jets (0.25-inch diameter) should be permanently mounted on the bow. One jet should be directed forward of the starboard bow, another should be directed forward of the area between the belts and the last should be directed forward of the port bow. Such jets would move the oil into one or both of the belts instead of allowing such oil to travel down between the hulls and the belts or between the belts themselves untouched. This would increase the oil recovery coverage between the hulls from seven feet (two belt widths) to the entire nine feet.

The fire pump onboard the vessel should be larger in order to handle the three small water jets and possibly larger ones extended out in front of the skimmer. The larger, boom-ounted water jets would be used to narrow a wide slick down to the 9 ft opening of the skimmer. The pump should be able to drive four 0.75-inch and three 0.25-inch diameter water jets at 100 psi.

A flexible 6-inch diameter hose, 6 ft long should be included in the skimmer's equipment to fit over the topside exhaust pipe to extend it down below water. The noise production of the skimmer would be greatly reduced.

The hydraulic drive unit for the center section should be enlarged since it was not possible to drive the belts at 6 knots while operating the offloading pumps and fire pump at full capacity. It may be possible to derive some power from the propulsion units in either catamaran hull since they are not used to their full capacity during oil recovery operations.

The brace which gives lateral strength to the rear roller belt guides should be moved further aft away from possible interference with the belts. An extension of the flat plate belt guides aft should not affect device performance.

The necessity of having a belt hold-down device on the skimmer should be examined. Since it appears that running the belt slightly faster than ZRV is most desirable, a device to ensure early belt contact with the water may not be necessary. During testing, the belt hold-down device often struck the oil slick and entrained the oil beyond the reach of the belts.

No debris tests were conducted during this test program. Such tests should be conducted using wood and ice as debris. An effort was put into developing a safety mechanism to protect the belt machinery should something cling to the belt and be brought over the rear drums. This should be tested further.

When lifting the assembled skimmer, it would be easier to use one large crane rather than two smaller ones. If two cranes must be used, it would be best to attach one crane to the forward pair of lifting eyes and one on the aft lifting eyes and stationed on the opposite side of the skimmer from its destination. The cranes can then lift vertically and boom down to move the skimmer. Two quick simple lifts in this manner would be less hazardous than stationing the two cranes at the bow and stern and then lifting, booming, and swinging at the same time. The lift may be completed in one operation using the latter method but the risks of damage are much higher. It should be noted that bomming down can position a load outside the safe lifting radius and thereby tip the crane. If the skimmer is to be moved beyond the safe lifting radius, it should be placed on the ground within the safe radius and the crane(s) moved closed to repeat the operation as often as necessary.

The use of scrapers as the primary means of removing oil from the belt should be examined. If most of the oil sorbed by the Astroturf portion of the belt remains on the outer layer of the belt, the inner felt liner could be removed and only one layer of Astroturf could suffice for the belt. This would reduce the cost of the belt. The wringer might be replaced by a sprocket drive incorporating a chain on the edge of the belt which would reduce the machinery costs.

The freeboard of the center section should be increased to allow more clearance during pitching and heaving. If the belt contacted the underside of the device during a test the shock would shake oil from the belt and entrain it beyond the reach of the belt.

APPENDIX A

FAST CURRENT OIL RECOVERY DESIGN GOALS
(As modified 22 January 1976)

Areas of Operation

a. Bays, Harbors, Estuaries
b. Coastal Rivers
c. Coastal Waters

Operational Environment

Up to 10 knots current with optional recovery in the 6 to 7 knot range and 2 foot confused seas with 20 knot winds.

Survival Environment

With Current

a. 15 knots current with calm sea
b. 10 knot current with 4 foot waves and 20 knot winds

Moored or Adrift

a. 6 foot wave height with 40 knot wind for one week

Minimum Oil Thickness

0.04 in.

Oil Type

Complete range of oils including distillate fuel oils, residual fuel, and crude oil with optimum recovery to be in the range of 10 cSt to 500 cSt.

Sea Temperature

+28°F to 100°F

Air Temperature

0°F to 120°F

Mode of Operation

Moored, towed and self-propelled

Transport from Central Storage to Nearest Port

One C-141 or two C-130's (two modules of 39' x 9' x 7' 10" LWH with a maximum weight of 25,000 pounds each)

Transport from Nearest Port to Scene

a. Self-Propelled
b. Towed by USCG or commercial vessel equal to or greater than a USCG 82 foot WPB
c. Carried on deck of USCG 180 WLB or a comparable commercial vessel

Power Supply

Included

Fuel Supply

12 hour endurance

System Integrity

Impervious to the environment and oil.

Cleanability

Easy to clean

System Support

a. Simple to assemble, install, load, launch, tend, refuel, maintain, operate, repair, and retrieve
b. Reliable
c. Assembly to be accomplished on scene in two hours

Control Function

System shall be capable of controlling oil so that it can be recovered.

Recovery Function

a. Throughput Efficiency greater than or equal to 95%
b. Recovery Efficiency greater than or equal to 75%
c. Recovery Rate up to and including 1000 gpm

Debris Handling/Protection Function

Shall be able to handle a moderate size and amount of debris.

Pump and Transfer Function

Pump up to 1000 gpm and not emulsify the oil.

Temporary Storage

Temporarily store 2000 gallons aboard and 500 long tons by external means.

APPENDIX B

OHMSETT TEST FACILITY

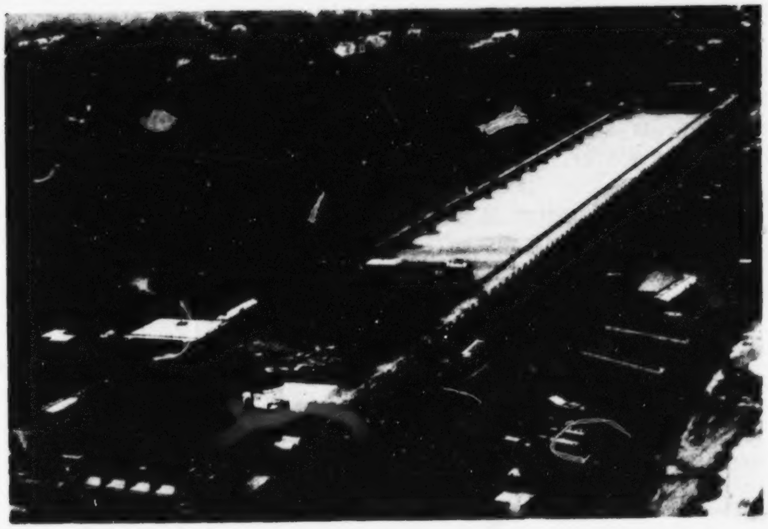


FIGURE B-1. OHMSETT TEST FACILITY.

GENERAL

The U.S. Environmental Protection Agency is operating an Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) located in Leonardo, New Jersey (Figure B-1). This facility provides an environmentally safe place to conduct testing and development of devices and techniques for the control of oil and hazardous material spills.

The primary feature of the facility is pile-supported, concrete tank with a water surface 667 feet long by 65 feet wide and with a water depth of 8 feet. The tank can be filled with fresh or salt water. It is usually filled from Sandy Hook Bay with water of 20 ppt salinity. The tank is spanned by a bridge capable of exerting a force up to 35,000 pounds, towing floating equipment at speeds to 6 knots for at least 45 seconds. Slower speeds yield longer test runs. The towing bridge is equipped to lay oil or hazardous materials on the surface of the water several metres ahead of the device being tested, so that reproducible thicknesses and widths of the test fluids can be achieved with minimum interference by wind.

The prinicpal systems of the tank include a wave generator and beach, and a filter system. The wave generator and adsorber beach have capabilities of producing regular waves to 2.25 feet high and to 92 feetlong, as well as a series of 4 feet high reflecting, complex waves meant to simulate the water surface of a harbor or the sea. The tank water is clarified by recirculation through a 2,000 gpm diatomaceous earth filter system to permit full use of a sophisticated underwater photography and video imagery system, and to remove the hydrocarbons that enter the tank water as a result of testing. The towing bridge has a built-in skimming barrier which can move oil onto the North end of the tank for cleanup and recycling.

When the tank must be emptied for maintenance purposes, the entire water volume, or (2.5 million gallons) is filtered and treated until it meets all applicable State and Federal water quality standards before being discharged. Additional specialized treatment may be used whenever hazardous materials are used for tests. One such device is a trailer-mounted carbon treatment unit for removing organic materials from the water.

Testing at the facility is served from a 6000 square feet building adjacent to the tank. This building houses offices, a quality control laboratory (which is very important since test fluids and tank water are both recycled), a small machine shop, and an equipment preparation area.

This government-owned, contractor-operated facility is available for testing purposes on a cost-reimbursable basis. The operating contractor, Mason & Hanger-Silas Mason Co., Inc., provides a permanent staff of twenty one multi-disciplinary personnel. The U.S. Environmental Protection Agency provides expertise in the area of spill control technology, and overall project direction.

For additional information, contact: Richard A. Griffiths, OHMSETT Project Officer, U.S. Environmental Protection Agency, Research and Development, MERL, Edison, New Jersey 08817, 201-321-6629.

APPENDIX C

TOW TEST DATA

TABLE C-1. USCG ZRV SKIMMER, CIRCO MEDIUM OIL

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
SD10	4.00	2.9	Calm	48.0	49.0	124	4.00	54	Discrete sampler is onboard the ZRV catch-all trough is mounted beneath the forward rollers.
SD11	4.00	2.9	Calm	47	70.7	177	4.00	54	Hole in catch-all trough dripping fluid in the center of the device to split the slick into the belts.
SD12	4.00	3.0	Calm	47	76.4	198	4.00	54	Bar in rear wringer assembly removed. Belt was losing fluid onto squeezed belt when it touched the bar.
SD13	4.00	3.0	Calm	48	74.1	191	4.00	54	Lowered rear drums 216 mm.
SD14	4.00	3.0	Calm	50	88.1	232	4.00	54	Replicate of SD13.
SD15	4.00	3.0	Calm	51	75.4	194	4.00	54	First precharge test, some oil was spilled over into the catch-all trough. Drums are lowered.
SD16	4.00	3.0	Calm	48	90.8	237	4.00	54	Same as SD15. Ran oil distribution 35 sec instead of 45 sec. Precharged with oil hose again. Stbd belt dripping water at front.

(Continued)

TABLE C-1. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
SD17	4.00	3.1	Calm	60	91.3	246	4.00	54	Collection barrels overflowed about 3 gallons of fluid. Port belt appears to be squeezed better than the stbd belt. Used precharge manifold.
SD18	4.00	3.1	Calm	64	82.5	221	4.00	54	Good test. 98% encounter.
SD19	4.00	3.2	Calm	68	98.0	269	4.5	54	Lower sump drain closed. +½ kt ZRV on the belts.
SD20	4.00	2.5	Calm	65	74.6	159	3.5	54	Lower sump drain closed -½ kt ZRV on the belts.
SD21	4.00	3.1	Calm	64	99.9	270	5.00	54	+1 kt ZRV test
SD22	4.00	3.1	Calm	65	103.8	278	3.00	54	-1 kt ZRV test
SD24	4.00	3.3	Calm	56	76.6	214	2.50	54	-1½ kt ZRV test
1	3.50	3.1	2.06 HC	56	84.4	185	3.50	54	Belt hold down device contacted waves at times.
2	3.50	3.0	2.06 HC	58	74.3	168	.50	54	Belt hold down device struck waves.

(Continued)

TABLE C-1. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
3	2.50	4.9	0.65, 38.0(b)	62	86.7	230	4.00	54	Bridge in slow down mode so the scheduled 4 kt, ZRV test became a 2 kt, + 1.5 kt test. Belt hold down device contacted waves lightly.
4	3.00	3.3	Calm	54	88.2	190	2.50	54	Center water jet working well.
5	3.50	3.1	Calm	70	90.6	216	3.00	54	Slick contacting inboard 85% of the belts.
6	3.50	3.1	1.04 HC	49	74.8	172	3.00	54	Center water jet rubber hose swung with movement of the vessel making zig zag in the oil.
7	1.00	1.1	Calm	35	82.3	18	0.75	54	Slick in the center 75% of the belts for the beginning ¼ of the test.
8	1.00	3.0	Calm	54	88.4	49	0.75	54	Slick predominantly on the stbd side of the vessel for ½ of the test.
9	1.00	5.1	Calm	58	77.4	77	0.75	54	Good test, some oil going down between the belts and the hulls.
10	2.00	1.3	Calm	52	73.4	40	1.50	54	Three small water jets on the bow of the skimmer. They are working well.

(Continued)

TABLE C-1. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
11	4.00	3.2	1.57 HC	54	68.4	187	3.50	54	99% encounter. Stbd belt ran to stbd on rear drum
12	4.00	3.1	Calm	57	84.5	225	3.50	54	Looked okay underwater.
13	2.00	5.2	Calm	90	54.6	123	1.50	54	100% encounter with the heavy slick.
14	2.00	3.1	Calm	85	91.5	122	1.50	54	Wind blowing center water jet off to side a little.
15	3.00	3.1	Calm	58	82.5	168	2.50	54	Even slick. Good test.
16	4.00	1.1	Calm	64	111.3	103	3.50	54	Oil distributed past normal cut off point.
16R	4.00	0.8	Calm	43	108.0	73	3.50	54	Good test.
17	4.00	3.0	Calm	55	70.4	184	3.50	54	Good test.
18-20									5 & 6 kt shakedown tests.
21	6.00	1.2	Calm	44	107.8	172	5.50	54	First 6 kt test - all went well.
22	4.00	4.7	Calm	58	59.7	241	3.50	54	Good test.
23									6 kt shakedown test - no oil.
24									6 kt shakedown test no oil - vessel squatted about 10 inches under tow.

(Continued)

TABLE C-1. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
25	6.00	2.8	Calm	48	50.9	185	5.50	54	Even slick across vessel. Belts rolling straight down into the water off the forward rollers.
26	6.00	3.0	Calm	46	53.8	212	5.50	57	Good test, but belts contacted the rear brace somewhat.
27	6.00	5.0	Calm	54	55.0	356	5.50	57	Even slick across belts.
28	5.00	3.0	Calm	72	61.7	202	4.50	57	Good tests. Belts did not strike the brace.
29	4.00	4.8	Calm	54	66.4	270	4.50	54	Three forward water jets working well. Good test.
30	4.00	3.2	Calm	54	75.2	211	3.50	54	Good test. Lost some oil from beneath the port belt. Stbd belt was red.
31	4.00	3.2	Calm	64	75.0	208	3.00	54	Good test. Even slick.
32	4.00	2.8	Calm	66	78.9	194	3.00	54	Duplicate of 31. Very little escaped between or down the sides of the belts.
33	4.00	2.8	Calm	70	88.3	213	4.00	54	Good test.
34	4.00	3.1	1.57 HC	50	67.9	182	3.50	54	Tied belt hold down device back to prevent it hitting the waves.
35	2.00	1.2	1.57 HC	41	104.0	53	1.50	54	Belts draping into the water. Slick is not even across the belts due to waves. Belts blotted up oil.

(Continued)

TABLE C-1. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
36	4.00	3.0	1.57 HC	47	61.7	159	3.50	54	Good test. Belt hold down device did not strike the waves.
37	6.00	1.1	1.57 HC	36	109.2	159	5.50	54	Belt hold down device occasionally struck the waves.
38	4.00	3.1	1.57 HC	49	65.5	173	3.50	54	Some belt hold down device contact with waves.
39	2.00	5.1	1.57 HC	57	82.3	182	1.50	54	Some contact between belt hold down device and waves. Surge of hulls converged the slick into the center 75% of the belts.
40	4.00	3.3	1.04 HC	48	84.4	238	3.50	54	Good test. Occasional slap of belts against the rear brace.
41	6.00	4.9	1.57 HC	43	41.8	262	5.50	60	Belt hold down device slapped waves occasionally.
42	4.00	3.7	2.26 HC	49	61.8	197	3.50	56	Great deal of surging of hulls and wave contact with belt hold device.
43	4.00	3.4	Calm	50	83.0	242	5.00	54	OK test.
110	6.00	5.0	1.18, 30.8	41	39.6	249	5.50	63	Belt hold down device struck waves. Hull surges caused oil slick disturbance.
111	6.00	1.0	1.18, 30.8	43	111.2	147	5.50	63	Interference with belt hold down device and hull surges.

(Continued)

TABLE C-1. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
112	2.00	1.0	1.18, 30.8	19	97.1	42	1.50	63	Wave reflection from vessel rolled forward into the slick and moving it to the center of the device.
113	4.00	3.0	1.18, 30.8	35	33.5	88	3.50	63	Belt hold down device is entraining oil.
114	4.00	3.1	1.18, 30.8	45	71.8	192	3.50	63	Repeat of 113. Belt hold down device struck waves. Oil appeared to adhere to belts better on this test.
115	2.00	5.0	1.18, 30.8	75	58.0	124	1.50	63	Surge moved slick to center - saturated inboard areas of belts.
116	4.00	3.0	1.18, 30.8	48	76.0	198	3.50	63	Some slick entrainment due to belt hold down device & hull surge, but a good test.
117	6.00	3.2	Calm	39	39.3	163	6.00	57	Fluid coming from belts at forward rollers. Belts scraped during the run.
118	6.00	3.2	Calm	64	53.7	223	6.00	57	Belts scraped again.
119	6.00	3.0	Calm	37	72.6	282	5.50	60	Bow rollers extended. Belt speed reduced. Still scraped a little.
120	6.00	3.0	Calm	48	70.1	275	5.50	66	Bow rollers extended. No scraping. Port belt lost oil behind. Stbd belt lost fluid at the forward rollers.

(Continued)

TABLE C-1. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
121	6.00	3.2	Calm	57	88.7	370	5.50	66	Repeat of 120 - Good test.
122	5.00	3.0	Calm	45	73.5	239	4.50	66	Fluid from forward rollers dripping on the slick.
123	4.00	3.0	Calm	50	92.0	237	5.50	54	Belts draping over the front. Good test. East wind blew most of the slick to the stbd side for ½ of the test. Hull surge causing oil to move to the center. Bow is pitching 0.75 m.
Air Jet Boom Tests #128 through 141 - Slick width --- 5.0 m wide.									
128	2.00	1.8	Calm	32	27.6	39	1.50	54	Air streams moved a good deal of oil into the center and down between the belts. The inner ¼ of each belt was saturated.
129	2.00	1.8	Calm	35	38.0	53	2.00	54	Air pressure reduced but oil is still going into the center and down between the belts. Some oil is being lost beneath the Air Jet boom.
130	3.00	1.7	Calm	26	45.6	92	3.00	54	Air pressure varied from 2.8 kg/cm^2 down.

(Continued)

TABLE C-1. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
131	4.00	1.7	Calm	42	41.4	114	3.50	54	Stbd air jet boom appears stronger than port. A rolling wave is helping to herd the slick.
132	4.00	1.7	Calm	33	50.4	132	3.50	54	Larger water jet in the center of the device. Air from booms disturbed smaller jet. Inner ⅓ of belts saturated, but no oil escaping between them. Booms moved closer to the bow of the skimmer.
133	4.00	1.7	Calm	38	35.5	99	3.50	54	Oil saturating inner 1/3 of belts.
134	4.00	1.8	Calm	52	55.4	157	3.50	54	Good test. Slight bow wave being made by aluminum connection helping to move oil.
135	4.00	1.7	Calm	42	46.6	123	3.50	54	Good test. Tow points holding cable for air jet boom are producing the rolling wave seen previously.
136									Aborted. Belts would not start.
137	6.00	1.7	Calm	30	52.0	205	5.50	54	Some oil passed beneath the air jet boom.
138	6.00	1.6	Calm	12	29.9	114	5.50	66	Belt extender out.

(Continued)

TABLE C-1. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR m^3/hr	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
139	4.00	1.8	Calm	29	13.9	39	3.50	53	Rags in ports of air jet to get higher flow from upstream ports.
140	4.00	1.7	Calm	24	48.9	128	3.50	53	Wake from air jet boom causing rolling wave which moves oil into the water jets. Belt scraped rear brace because belt hold down device was not engaged.
141	4.00	1.7	Calm	31	56.9	151	3.50	53	Tow points and aluminum connection pieces producing rolling wakes. Wind blowing oil into port air jet.
142	6.00	3.1	Calm	24	54.3	215	5.50	65	Uneven slick. Stbd belt speed fell from 5.5 to 5 knots at the end of the test.
143	6.00	3.1	Calm	27	56.3	222	5.50	65	Narrative not available.
144	6.00	3.1	Calm	23	69.4	288	5.50	65	Good test.
145	4.00	3.1	Calm	60	85.6	231	2.50	54	Slow belt speed caused headwave to develop in front of the belts. This pushed oil to the center of the device.
146	4.00	3.2	2.26 HC	34	49.5	130	3.50	65	OK test.

(Continued)

TABLE C-1. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
Water Jet Tests #154 through 168 - Slick Width was 5.45 m									
154	2.00	1.4	Calm	73	79.4	92	1.50	53	Water Jet test #154 through 168 - slick width was 5.45 m. All oil appears to be directed inside the skimmer's center section.
155	4.00	1.5	Calm	31	60.3	161	3.50	53	Some oil is missing outside the bows.
156	6.00	1.6	Calm	23	33.8	137	5.50	65	Bow waves by the hulls were brownish-pink indicating the oil was not moved far enough to reach the center section of the skimmer.
157	2.00	1.5	1.57 HC	38	55.5	74	1.50	59	Water jet pressure was reduced from 2.8 kg/cm^2 to 2.1 kg/cm^2. The higher pressure was pushing the oil too far into the center.
158	4.00	1.5	2.26 HC	24	56.5	150	3.50	59	Most of the oil was moved into the center section of the skimmer.
159	4.00	1.5	1.57 HC	28	59.4	157	3.50	59	Water jet pressure at 5.6 kg/cm^2 (maximum)
160	4.00	1.5	Calm	34	61.5	157	3.50	59	Narrative not available.

(Continued)

TABLE C-1. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
161									Presoak test to determine how much oil could be extracted from the belts if no oil was distributed.
162	6.00	1.5	1.57 HC	34	53.2	205	5.50	59	Good test.
163	6.00	1.5	1.57 HC	22	40.0	164	5.50	64	OK test.
164	6.00	1.5	1.57 HC	34	53.9	210	5.50	64	OK. Repeat of 163.
165	4.00	1.6	2.26 HC	28	63.1	182	3.50	64	Good test.
166	4.00	1.6	Calm	36	57.2	160	3.50	54	Narrative not available.
167	2.00	1.5	Calm	29	69.4	84	1.50	54	The skimmer fire pump supplied the water to the water jets.
168	4.00	1.5	Calm	33	64.4	167	3.50	54	Two water jets on each boom were used.
169	3.00	10.0	Calm	67	55.5	351	4.00	54	Heavy slick test with a fast belt to try to obtain the maximum oil recovery rate.
170	6.00	3.1	1.57 HC	56	81.1	326	5.50	64	Good test.

TABLE C-2. USCG ZRV SKIMMER, CIRCO X HEAVY OIL

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
44	2.00	3.2	Calm	48	51.3	68	1.50	54	Lost oil outside of hulls and between belts and hulls. Slick was uneven.
45	2.00	3.1	Calm	69	77.9	104	1.50	54	Repeat of 44 to saturate belts with heavy oil. Underwater view of slick is good.
46	2.00	3.1	Calm	75	86.8	114	1.50	54	Repeat of test 44. Slick was even. Water jets worked well.
47	3.00	2.9	Calm	53	96.0	181	2.50	54	Even slick. Good test.
48	2.00	4.8	Calm	78	65.0	132	1.50	54	OK test.
49	4.00	1.2	Calm	36	121.4	128	3.50	54	Good test.
50	4.00	3.4	Calm	59	90.9	262	3.50	54	Oil remained in a good tight slick. Bridge water jets were almost not needed.
51	4.00	4.9	Calm	61	66.9	281	3.50	54	Good test.
52	4.00	5.2	Calm	56	73.3	326	4.50	54	Port belt received a little more oil than the stbd belt.
53	4.00	3.1	2.26 HC	60	72.0	191	4.50	54	Large harbor chop caused severe pitch. Belt hold down device struck the waves.

(Continued)

TABLE C-2. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
54	2.00	3.1	1.57 HC	49	59.5	76	1.50	54	Uneven slick due to wave action. Little entrainment.
55	2.00	3.1	1.57 HC	51	93.4	126	2.50	54	Uneven slick, some entrainment of oil. Hull surging is forcing oil towards the center of the device.
56	2.00	3.1	1.57 HC	47	80.6	108	1.50	60	Uneven slick shifted from port to stbd belt. Belt hold down device tied back.
57	6.00	3.1	Calm	52	95.1	384	5.50	57	Belt hold down device tied back. OK test.
58	6.00	3.5	Calm	50	50.9	228	5.50	57	Vessel had slight yaw to port.
59	6.00	3.1	1.57 HC	52	65.1	263	5.50	57	Belt hitting the rear cross brace periodically.
60	4.00	3.0	1.57 HC	54	93.7	242	3.50	57	Stbd belt struck rear brace periodically.
61	4.00	3.2	1.57 HC	36	62.0	170	3.50	60	OK test. Forward rollers extended to take up belt slack.
62	4.00	1.1	1.57 HC	46	140.8	141	3.50	60	Good test with almost no oil left behind.

(Continued)

TABLE C-2. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
63	4.00	5.0	1.57 HC	47	45.5	195	3.50	60	Stbd belt looks splotchy, compared to port. Inboard areas of belts coated well due to hulls surging and moving slick to the center.
64	6.00	3.2	1.57 HC	46	64.9	271	5.50	60	Good test.
65	6.00	3.0	1.57 HC	49	61.4	239	6.00	60	Good test. Water jets working well.
66	4.00	3.0	1.04 HC	43	76.8	200	3.50	60	Small harbor chop does not entrain very much oil.
67	4.00	3.1	Calm	68	95.6	252	3.50	60	Some oil was washing on top of the belts as it passed between them and the hulls. OK test.
68	4.00	3.1	Calm	48	92.3	248	4.00	60	Good test.
69	4.00	3.2	Calm	50	87.4	236	4.00	60	Good test.
70	4.00	3.0	Calm	70	68.5	179	3.50	60	Belts appear a little splotchy. First test after the weekend.
71	4.00	3.1	Calm	63	82.2	220	3.50	60	Repeat of 70 - good test.
72	4.00	3.0	1.57 HC	45	74.3	193	3.50	60	99% encounter - OK test.
73	4.00	3.0	2.26 HC	33	52.4	136	3.50	60	Hull surging is driving oil towards the center of the device.

(Continued)

TABLE C-2. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
124	2.00	3.1	1.18, 30.8	41	64.9	88	1.50	62	East wind moved the slick over to the stbd side a bit for ½ the test run.
125	6.00	3.2	1.18, 30.8	47	40.7	167	5.50	62	Hull surge causing oil to move to the center. Bow is pitching 0.75 m.
126	4.00	5.0	1.18, 30.8	72	64.3	274	3.50	62	Hull surge concentrating oil into the center.
127	4.00	1.0	1.18, 30.8	44	197.6	177	3.50	62	OK test.

TABLE C-3. USCG ZRV SKIMMER, CIRCO 4X LIGHT OIL

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
74	4.00	2.9	Calm	43	72.9	183	3.50	60	Good slick. Not much entrainment of the light oil.
75	4.00	2.5	Calm	42	64.7	139	3.50	60	100% encounter - Good test.
76									Aborted. Ran out of oil during the test.
77	4.00	4.0	Calm	38	50.4	172	3.50	60	Heavier slick in the center.
78	4.00	3.4	Calm	42	55.9	161	3.50	60	Repeat of 77. Slick better due to change in width of oil distribution manifold.
79	2.00	3-4.7[(a)]	Calm	60	77.1	150	2.50	60	Slick was varied to observe losses at the rear of the device. Port belt lost a bit more oil than the stbd.
80	2.00	3-5.3	Calm	55	65.0	143	2.50	60	Slick varied to observe progressive losses from belts at the rear drums. Oil slick driven completely to port during middle of test.
81	2.00	3-6.3	Calm	44	70.9	174	2.50	60	Repeat of 80 with an even slick. Rear drums filmed. Port belt lost a slight bit more oil, but not much.

(Continued)

TABLE C-3. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
82	2.00	3.1	Calm	30	51.5	70	2.00	60	Underwater filming of the belts by diver under tow. Such filming probably detracted from skimmer performance.
83	2.00	3.7	Calm	26	33.3	51	2.00	60	Underwater filming.
84	2.00	5.1	Calm	28	40.2	84	3.50	60	Underwater filming.
85	2.00	1.2	Calm	68	354.5	180	1.50	60	Vessel not cleared of oil after presoak.
86	2.00	1.0	Calm	66	261.6	114	1.50	60	Oil probably still very heavy on the belts.
87	2.00	3.3	Calm	58	55.5	78	2.50	54	Prewet 100 gallons prior to test.
88	4.00	1.3	Calm	35	127.9	147	3.50	54	Wind is blowing the slick from side to side. It is raining.
89	2.00	1.1	Calm	29	82.6	39	1.50	54	Slick down the inboard portion of the belts. Raining.
90	2.00	5.1	Calm	73	61.0	132	1.50	54	Good slick. OK test.
91	3.00	3.1	Calm	44	97.8	198	2.50	54	Cross winds blowing center water jet making zig zag in slick.
92	4.00	3.0	Calm	36	86.6	225	3.50	54	OK test.
93	4.00	4.8	Calm	47	56.3	228	3.50	54	Started tests without slick herding jets on, but recovered okay. 97% encounter.

(Continued)

TABLE C-3. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
94	4.00	4.8	Calm	45	55.9	228	4.50	54	Stbd belt mistracked and was shut down.
95	4.00	5.2	Calm	45	94.3	416	4.50	54	Repeat of 94. All looked good.
96	4.00	3.1	Calm	33	65.6	175	4.50	54	Good test.
97	6.00	1.2	Calm	22	76.7	124	5.50	54	Good test.
98	6.00	3.1	Calm	34	83.1	330	5.50	54	Good test. A good deal of excess fluid coming off from the front rollers into the trough overflowing it slightly.
99	6.00	5.2	Calm	46	70.3	469	5.50	54	Good test. Fluid being lost from port belt at forward rollers.
100	5.00	3.1	Calm	44	89.9	298	4.50	54	OK test.
101	4.00	1.0	1.18, 30.8	38	131.6	110	3.50	54	Hull surge drives oil to the center of the device. Belts are blotting up the oil well. Belts struck rear brace.
102	4.00	1.0	1.18, 30.8	30	88.5	80	3.50	57	Extended forward rollers. Some scraping of stbd belt on rear brace.
103	4.00	1.0	1.18, 30.8	27	89.9	80	3.50	60	Extended rollers again. Still slight scraping.

(Continued)

TABLE C-3. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
104	2.00	3.1	1.18, 30.8	31	72.0	95	1.50	60	Slight scraping, but good test.
105	4.00	1.0	1.18, 30.8	20	99.1	90	3.50	65	Forward rollers out further. Belts did not leave the rear drums.
106	4.00	1.1	1.18, 30.8	35	101.3	91	3.50	63	Front rollers brought in. No scraping. Belt hold down device is tied back.
107	2.00	3.2	1.18, 30.8	40	65.8	89	1.50	63	Pitching drives oil to the center. Belts are saturated on their inboard halves.
108	6.00	3.1	1.18, 30.8	32	61.6	244	5.50	63	Belt hold down device is tied back but is contacting the waves. Pitching very pronounced.
109	4.00	4.8	1.18, 30.8	37	71.5	295	3.50	63	Belt hold down device struck a little, but it was a good test.
147	2.00	3.2	1.57 HC	26	22.3	30	1.50	54	Wave coming forward from device is rolling into the slick. Belt scraped on rear brace.
148	2.00	3.0	1.57 HC	41	79.1	101	1.50	60	Forward rollers extended. Repeat of 147. Good test.
149	4.00	1.0	1.57 HC	19	131.5	116	3.50	60	

(Continued)

TABLE C-3. (CONTINUED)

Test no.	Tow spd. (kts)	Slick thk. (mm)	Wave	RE %	TE %	ORR gpm	Belt spd. (kts)	Fwd Roller Ext. (in)	Comments
150	6.00	3.2	1.57 HC	36	72.4	290	5.50	60	OK test.
151	2.00	3.0	Calm	25	61.1	78	1.50	54	OK test. Loss from the belts looked to be equal.
152	4.00	10.4	Calm	54	53.3	470	5.00	54	Good test.
153	4.00	4.5	1.57 HC	43	76.8	300	3.50	54	OK test.

APPENDIX D

TABLE D-1. USCG ZRV SKIMMER DRAG CHARACTERISTICS

Test no.	Speed knots	Resistance	Comments
SD 1	1	20	
SD 2	1	10	
8	1	50	Eliminate
9	1	10	

Average 13.33
Standard Deviation 5.77

Test no.	Speed knots	Resistance	Comments
SD 3	2	100	
SD 6	2	80	
13	2	70	
14	2	40	
44	2	20	
45	2	30	
46	2	20	
79	2	60	
80	2	70	
81	2	40	
82	2	40	
83	2	70	
84	2	70	
85	2	100	
86	2	90	
89	2	30	
90	2	80	
128	2	30	
129	2	10	
159	2	70	
167	2	40	

Average 55.2
Standard Deviation 27.32

Test no.	Speed knots	Resistance	Comments
SD 4	3	200	
SD 7	3	290	
4	3	260	
15	3	200	
47	3	150	
41	3	210	
169	3	220	

Average 211.6
Standard Deviation 45.25

(Continued)

TABLE D-1. (Continued)

Test no.	Speed knots	Resistance	Comments
SD 5	4	1140	Eliminate
SD 9	4	500	
SD10	4	940	Eliminate
SD11	4	610	
SD12	4	550	
SD13	4	530	
SD14	4	440	
SD15	4	380	
SD16	4	450	
SD17	4	600	
SD18	4	530	
SD19	4	620	
SD20	4	600	
SD21	4	680	
SD22	4	580	
SD23	4	800	
SD24	4	500	
12	4	480	
16	4	590	
17	4	570	
22	4	520	
24	4	530	
30	4	520	
32	4	560	
33	4	530	
43	4	470	
49	4	560	
50	4	840	Eliminate
51	4	260	Eliminate
52	4	610	
69	4	440	
67	4	Edit	
68	4	510	
71	4	410	
74	4	530	
75	4	580	
76	4	540	
77	4	550	
78	4	510	
88	4	490	
92	4	450	
93	4	500	
94	4	540	
95	4	470	
96	4	520	

(Continued)

TABLE D-1. (Continued)

Test no.	Speed knots	Resistance	Comments
123	4	730	Eliminate
131	4	350	
132	4	480	
133	4	320	
134	4	380	
139	4	310	
141	4	200	Eliminate
152	4	550	
161	4	530	
166	4	480	
168	4	420	
Average 506.4			
Standard Deviation 82.11			
18	5	920	
28	5	820	
100	5	800	
122	5	1090	
136	5	1010	
136R	5	820	
Average 910			
Standard Deviation 119.0			
19	6	1560	
20	6	1500	
21	6	1590	
23	6	1670	
24	6	1420	
25	6	1080	
26	6	1760	
27	6	1420	
57	6	1270	
58	6	1470	
97	6	1140	
98	6	1850	
99	6	1470	
117	6	1960	
118	6	1980	
119	6	2010	

(Continued)

TABLE D-1. (Continued)

Test no.	Speed knots	Resistance	Comments
120	6	2010	
121	6	1970	
137	6	1510	
138	6	1490	
142	6	1450	
143	6	1750	
144	6	1870	
156	6	1340	

Average 1630.4
Standard Deviation 262.54

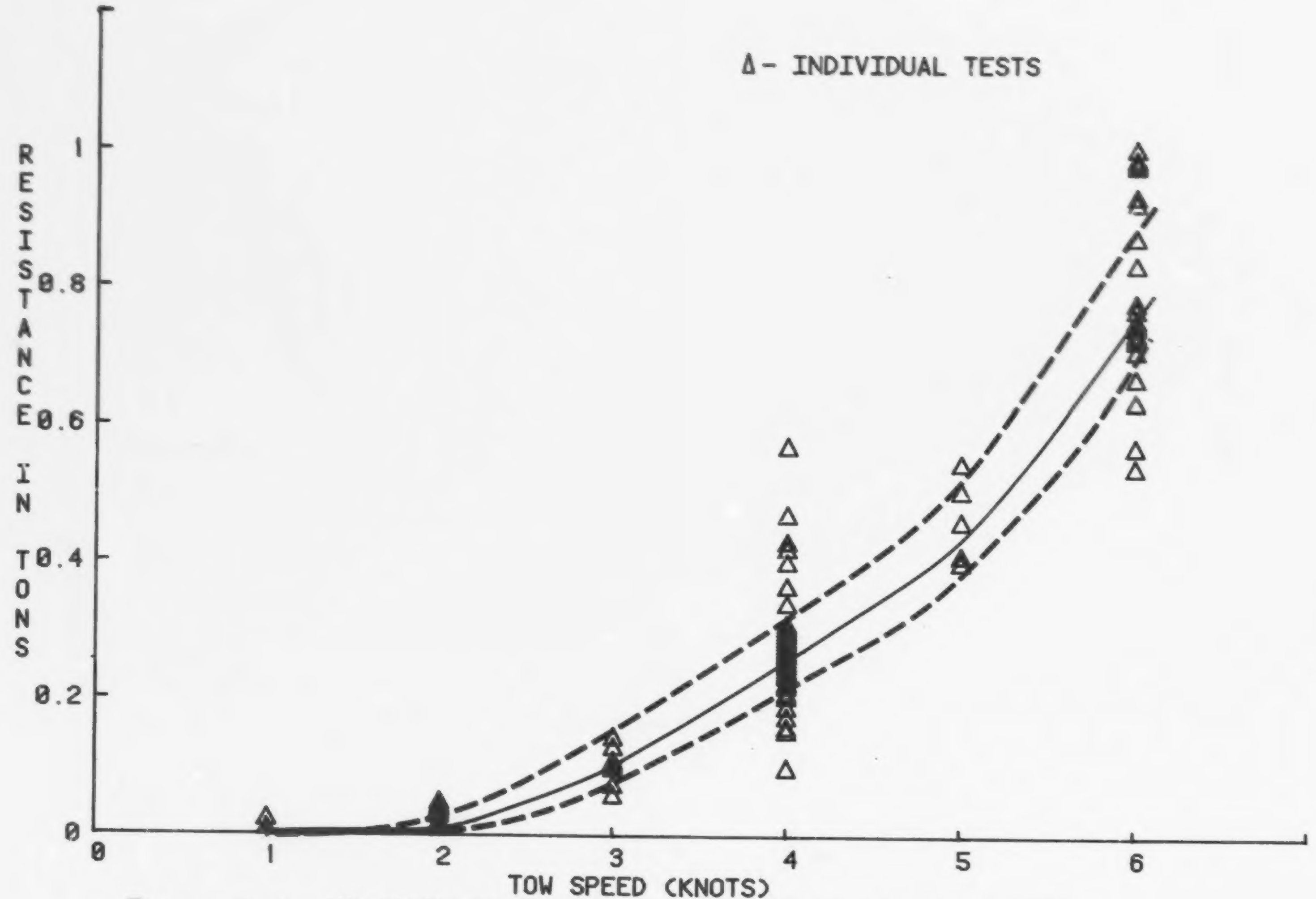


Figure D-1 : US COAST GUARD ZRV SKIMMER RESISTANCE AS MEASURED DURING OHMSETT TESTS.

APPENDIX E

BOX-BEHNKEN ANALYSIS

A Box-Behnken type of experimental design is employed to determine with some precision the shape of the experimental space in which the experiment was conducted. The results of the experiment may be interpolated with some confidence within the experimental space, but extrapolation is strongly discouraged. Box Behnken designs require a minimum of experimental trials to yield sufficient data to construct a quadratic model of the response being investigated.

The design employed here was a 2^3 balanced incomplete block design. The results of the analysis yield a response surface equation which may be used to determine the value of the dependent variable at any point within the experimental region. Usually the results are employed to find a maximum or minimum for the variable(s) of interest.

The computer printouts for each set of data shows the raw data and the transformed values of the X_i data points. The -1 corresponds to the lowest value for the range tested. Using tow speed as an example: -1 is equivalent to 2 knots, 0 is equivalent to 4 knots and +1 is equivalent to 6 knots.

Next, the quadratic equation of the response surface is presented and then the values of the coefficients are given.

The last part of the printout is an analysis of the residuals for the given equation, and finally, the residual is displayed. The residual is the difference between the actual and calculated Y values.

The final values which are displayed are: the variance and standard deviation of the residuals; the multiple correlation coefficient, R2; the F ratio for R2; and the degrees of freedom for the numerator (D.O.F.1) and denominator (D.O.F.2) of the F ratio. Also indicated is the appropriate F value from a table, to determine the significance of R2.

R2 shows the degree of fit of the model to the given data and can be thought of as the percentage of the data which is explained by the model. The F ratio, when tested against the appropriate value in an F table, gives an indication of how much confidence we can place in the model. If the F test is significant, i.e., the value of F from the table is less than the computed F value, we can place a good deal of confidence in the model, and use it as a basis for prediction of the response under any set of conditions within the experimental space.

What follows will be an interpretation of one of the data sets in which the results are rather clear-cut. The data we will consider are for oil recovery (GPM) in calm seas. The computer printout presents the coefficients for the quadratic equation and the analysis of the residuals.

An examination of the computer printout shows a standard deviation of 19.118, and it can be seen from an examination of the residuals that only a few of them are greater than this value. R2 = 0.968 which means that 96.8% of the data is explained by the response surface equation. The F ratio of 12.127 is significant and is beyond the .001 level which means that there is less than a 1 in 1000 chance that the results obtained in this experiment occurred by chance.

The plots of the data show values calculated from the response surface equation at all points. The larger number circles (1-13) are the values for actual experimental points, while the smaller circles have values which fill out the corner points of the cubic experimental space. The variables along the axes are names and the transformed range of values for each variable is indicated.

To understand the data, one can look at the way in which values of the dependent variable change from one face of the cube to another, e.g., from the front face to the back face, which would explain the effect of tow speed. For oil recovery in calm seas, there is a very clear effect which says that the higher the tow speed, the greater the rate of oil recovery. This is not to say that viscosity and slick thickness don't have an effect, but for any particular combination of conditions increasing the tow speed increases the rate of recovery of oil. The actual rate of recovery will depend on the particular values of the other independent variables.

Two sets of data which need special attention are the oil recovery and throughput efficiency for regular seas. Both of these sets of data seem to have a center point which is grossly in error. In the case of oil recovery, it is well over 2 standard deviations away from the mean, which is very unlikely. Furthermore, the variance for this set of data appears to be significantly greater than for other sets of similar data. Therefore, an analysis was performed with the point removed. This results in the variance of the residuals falling in line with the other data sets, the correlation coefficient is much larger and it is significant. Thus the elimination of the point seems to have been reasonable. The same point was eliminated from the throughput efficiency data for regular seas and while the variance was reduced, the R2 and F increased, the results are still not significant and extreme caution should be used regarding any conclusions drawn from this data or the response surface equation for these data.

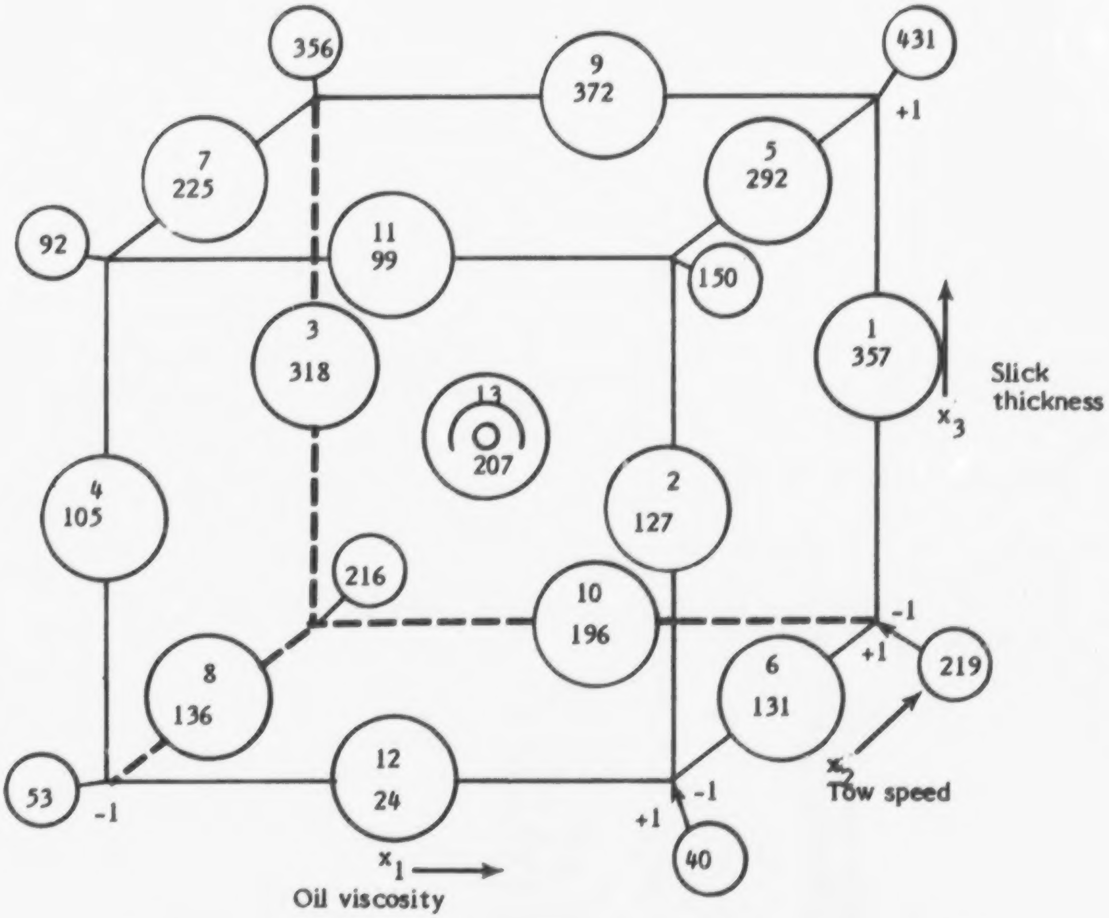

356
9
372
431
+1
7
225
5
292
92
11
99
150
3
318
1
357
Slick thickness
x_3
13
207
4
105
2
127
216
10
196
-1
8
136
6
131
+1
219
12
24
53
-1
-1
+1
x_2
Tow speed
40
x_1
Oil viscosity

FIGURE E-1. CALM SEAS - OIL RECOVERY (GPM) BOX BEHNKEN DIAGRAM.

CALM SEAS - OIL RECOVERY RATE (GPM)

Y-Data	BOX BEHNKEN DESIGN MATRIX FOR 3 VARIABLES					
384.000	*	*	*	1	1	0
114.600	*	*	*	1	-1	0
330.600	*	*	*	-1	1	0
78.100	*	*	*	-1	-1	0
281.000	*	*	*	1	0	1
127.900	*	*	*	1	0	-1
228.500	*	*	*	-1	0	1
146.700	*	*	*	-1	0	-1
356.400	*	*	*	0	1	1
172.400	*	*	*	0	1	-1
122.800	*	*	*	0	-1	1
40.200	*	*	*	0	-1	-1
225.300	*	*	*	0	0	0
184.000	*	*	*	0	0	0
211.500	*	*	*	0	0	0

X_1 = oil viscosity
X_2 = tow speed
X_3 = slick thickness

Definitions apply to all tests.

COEFFICIENTS TO QUADRATIC EQUATION

Y = B1 + B2*(X1)**2 + B3*(X2)**2 + B4*(X3)**2 + B5*X1 + B6*X2 + B7*X3 + B8*X1*X2 + B9*X1*X3 + B10*X2*X3

B(1) = 206.933
B(2) = 21.483
B(3) = -1.592
B(4) = -32.392
B(5) = 15.450
B(6) = 110.962
B(7) = 62.688
B(8) = 4.225
B(9) = 17.825
B(10) = 25.350

Pt. No.	Actual Y	Approx. Y	Residual
1	384.000	357.462	26.538
2	114.600	127.088	-12.488
3	330.600	318.113	12.487
4	78.100	104.638	-26.538
5	281.000	291.988	-10.988
6	127.900	130.962	-3.062
7	228.500	225.438	3.062
8	146.700	135.712	10.988
9	356.400	371.950	-15.550
10	172.400	195.875	-23.475
11	122.800	99.325	23.475
12	40.200	24.650	15.550
13	225.300	206.933	18.367
14	184.000	206.933	-22.933
15	211.500	206.933	4.567

Variance	Std. Dev.	R2	F	D.O.F.1	D.O.F.2
365.507	19.118	0.968	12.127	4	10

$F_{.001} = 11.28$

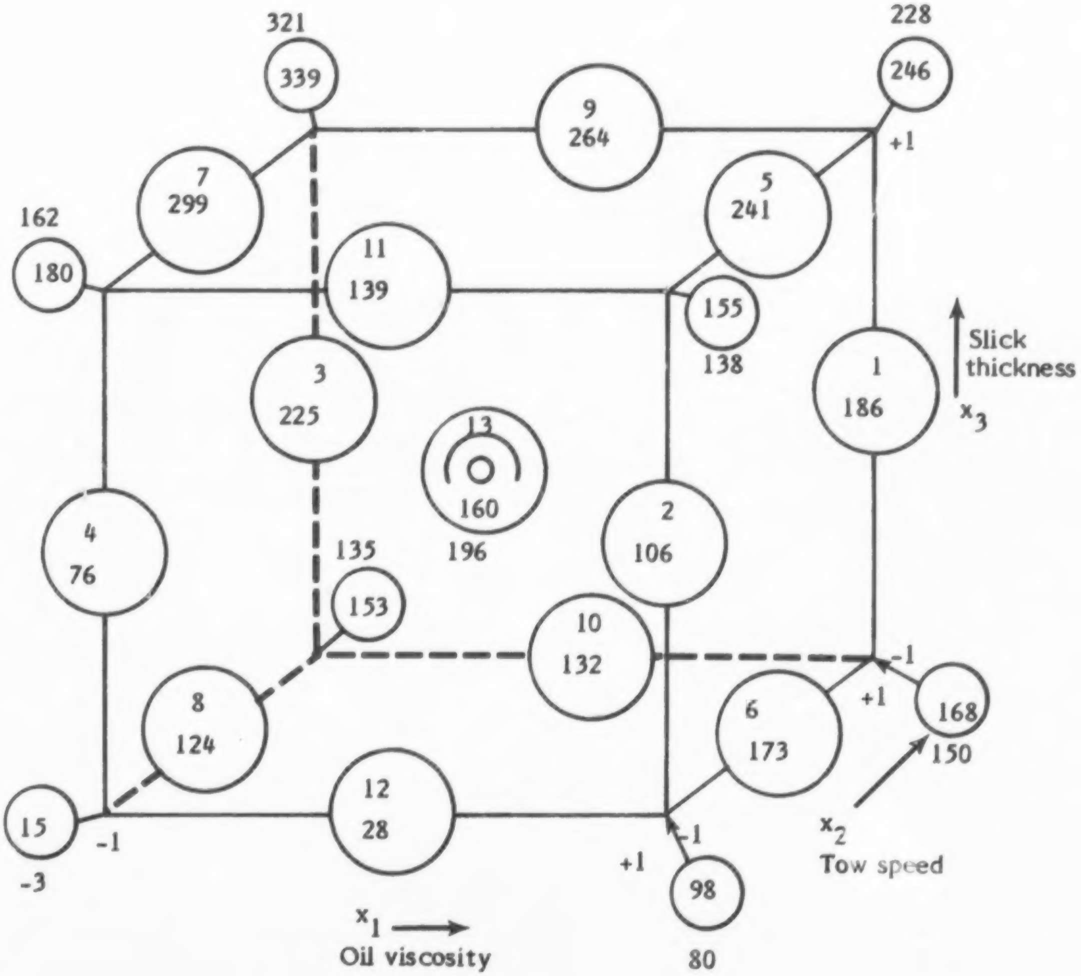

321
339
228
246
9
264
+1
7
299
5
241
162
180
11
139
155
138
Slick thickness
1
186
x_3
3
225
13
160
196
2
106
4
76
135
153
10
132
-1
8
124
6
173
+1
168
150
12
28
15
-1
-3
-1
+1
98
80
x_2
Tow speed
x_1
Oil viscosity

FIGURE E-2. REGULAR SEAS - OIL RECOVERY (GPM) BOX BEHNKEN DIAGRAM.

```
                REGULAR SEAS - OIL RECOVERY RATE (GPM)

Y-Data          BOX BEHNKEN DESIGN MATRIX FOR 3 VARIABLES

 166.800      *        *        *       1        1        0
  87.900      *        *        *       1       -1        0
 243.100      *        *        *      -1        1        0
  95.500      *        *        *      -1       -1        0
 273.900      *        *        *       1        0        1
 177.300      *        *        *       1        0       -1
 295.300      *        *        *      -1        0        1
  91.300      *        *        *      -1        0       -1
 249.600      *        *        *       0        1        1
 146.800      *        *        *       0        1       -1
 123.900      *        *        *       0       -1        1
  42.100      *        *        *       0       -1       -1
  88.500      *        *        *       0        0        0
 192.500      *        *        *       0        0        0
 198.700      *        *        *       0        0        0

                 COEFFICIENTS TO QUADRATIC EQUATION

Y = B1 + B2*(X1)**2 + B3*(X2)**2 + B4*(X3)**2 + B5*X1 + B6*X2 + B7*X3 +
B8*X1*X2 + B9*X1*X3 + B10*X2*X3

              B( 1)        =     159.900
              B( 2)        =      28.637
              B( 3)        =     -40.212
              B( 4)        =      20.913
              B( 5)        =      -2.413
              B( 6)        =      57.113
              B( 7)        =      60.650
              B( 8)        =     -17.175
              B( 9)        =     -26.850
              B(10)        =       5.250
```

Pt. No.	Actual Y	Approx. Y	Residual
1	166.800	185.850	-19.050
2	87.900	105.975	-18.075
3	243.100	225.025	18.075
4	95.500	76.450	19.050
5	273.900	240.837	33.062
6	177.300	173.238	4.062
7	295.300	299.363	-4.062
8	91.300	124.363	-33.063
9	249.600	263.613	-14.013
10	146.800	131.813	14.987
11	123.900	138.887	-14.988
12	42.100	28.088	14.012
13	88.500	159.900	-71.400
14	192.500	159.900	32.600
15	198.700	159.900	38.800

Variance	Std. Dev.	R2	F	D.O.F.1	D.O.F.2
864.756	29.407	0.855	2.353	4	10

$F_{.05} = 3.48$

```
                    REGULAR SEAS - OIL RECOVERY RATE (GPM)
Y-Data          BOX BEHNKEN DESIGN MATRIX FOR 3 VARIABLES

 166.800        *        *        *        1        1        0
  87.900        *        *        *        1       -1        0
 243.100        *        *        *       -1        1        0
  95.500        *        *        *       -1       -1        0
 273.900        *        *        *        1        0        1
 177.300        *        *        *        1        0       -1
 295.300        *        *        *       -1        0        1
  91.300        *        *        *       -1        0       -1
 249.600        *        *        *        0        1        1
 146.800        *        *        *        0        1       -1
 123.900        *        *        *        0       -1        1
  42.100        *        *        *        0       -1       -1
 192.500        *        *        *        0        0        0
 198.700        *        *        *        0        0        0

                   COEFFICIENTS TO QUADRATIC EQUATION

Y = B1 + B2*(X1)**2 + B3*(X2)**2 + B4*(X3)**2 + B5*X1 + B6*X2 + B7*X3 +
B8*X1*X2 + B9*X1*X3 + B10*X2*X3

               B( 1)        =      195.600
               B( 2)        =       10.787
               B( 3)        =      -58.062
               B( 4)        =        3.063
               B( 5)        =       -2.413
               B( 6)        =       57.113
               B( 7)        =       60.650
               B( 8)        =      -17.175
               B( 9)        =      -26.850
               B(10)        =        5.250
```

Pt. No.	Actual Y	Approx. Y	Residual
1	166.800	185.850	-19.050
2	87.900	105.974	-18.074
3	243.100	225.026	18.074
4	95.500	76.450	19.050
5	273.900	240.837	33.063
6	177.300	173.237	4.063
7	295.300	299.363	-4.063
8	91.300	124.363	-33.063
9	249.600	263.614	-14.014
10	146.800	131.814	14.986
11	123.900	138.888	-14.988
12	42.100	28.088	14.012
13	192.500	195.600	-3.100
14	198.500	195.600	3.100

Variance	R2	F	D.O.F.1	D.O.F.2
343.050	0.942	4.885	3	10

S.D. = 18.522

$F_{.025} = 4.83$

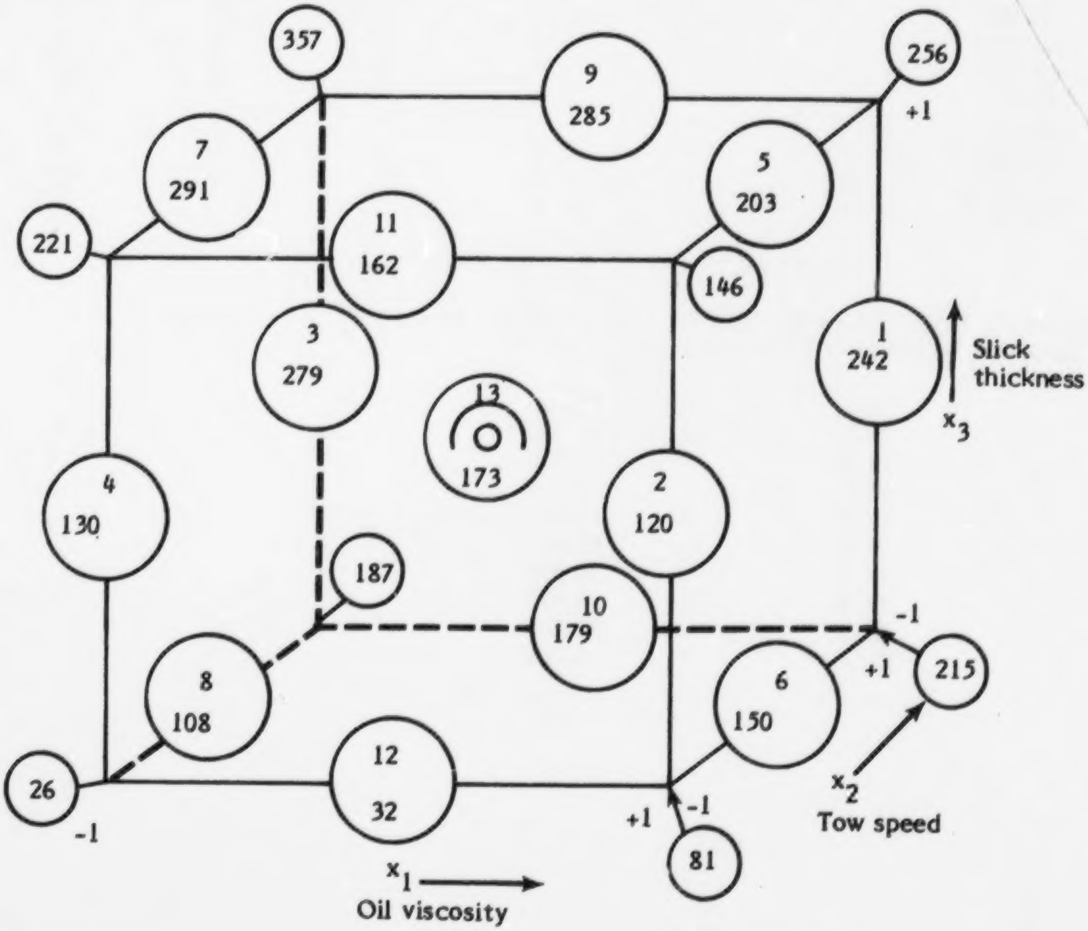

357
9
285
256
+1
7
291
5
203
221
11
162
146
3
279
1
242
Slick thickness
x_3
13
173
4
130
2
120
187
10
179
-1
8
108
6
150
+1
215
12
32
26
-1
+1
-1
81
x_2
Tow speed
x_1
Oil viscosity

FIGURE E-3. HARBOR CHOP - OIL RECOVERY (GPM) BOX BEHNKEN DIAGRAM.

HARBOR CHOP - OIL RECOVERY RATE (GPM)

Y-Data	BOX BEHNKEN DESIGN MATRIX FOR 3 VARIABLES					
271.400	*	*	*	1	1	0
108.500	*	*	*	1	-1	0
290.800	*	*	*	-1	1	0
101.300	*	*	*	-1	-1	0
195.000	*	*	*	1	0	1
140.800	*	*	*	1	0	-1
300.100	*	*	*	-1	0	1
116.300	*	*	*	-1	0	-1
263.800	*	*	*	0	1	1
159.400	*	*	*	0	1	-1
182.100	*	*	*	0	-1	1
52.900	*	*	*	0	-1	-1
187.700	*	*	*	0	0	0
158.800	*	*	*	0	0	0
173.700	*	*	*	0	0	0

COEFFICIENTS TO QUADRATIC EQUATION

Y = B1 + B2*(X1)**2 + B3*(X2)**2 + B4*(X3)**2 + B5*X1 + B6*X2 + B7*X3 + B8*X1*X2 + B9*X1*X3 + B10*X2*X3

B(1) = 173.400
B(2) = 21.550
B(3) = -1.950
B(4) = -6.900
B(5) = -11.600
B(6) = 67.575
B(7) = 58.950
B(8) = -6.650
B(9) = -32.400
B(10) = -6.200

Pt. No.	Actual Y	Approx. Y	Residual
1	271.400	242.325	29.075
2	108.500	120.475	-11.975
3	290.800	278.825	11.975
4	101.300	130.375	-29.075
5	195.000	203.000	-8.000
6	140.800	149.900	-9.100
7	300.100	291.000	9.100
8	116.300	108.300	8.000
9	263.800	284.875	-21.075
10	159.400	179.375	-19.975
11	182.100	162.125	19.975
12	52.900	31.825	21.075
13	187.700	173.400	14.300
14	158.800	173.400	-14.600
15	173.700	173.400	0.300

Variance	Std. Dev.	R2	F	D.O.F.1	D.O.F.2
312.512	17.678	0.943	6.579	4	10

$F_{.01} = 5.99$

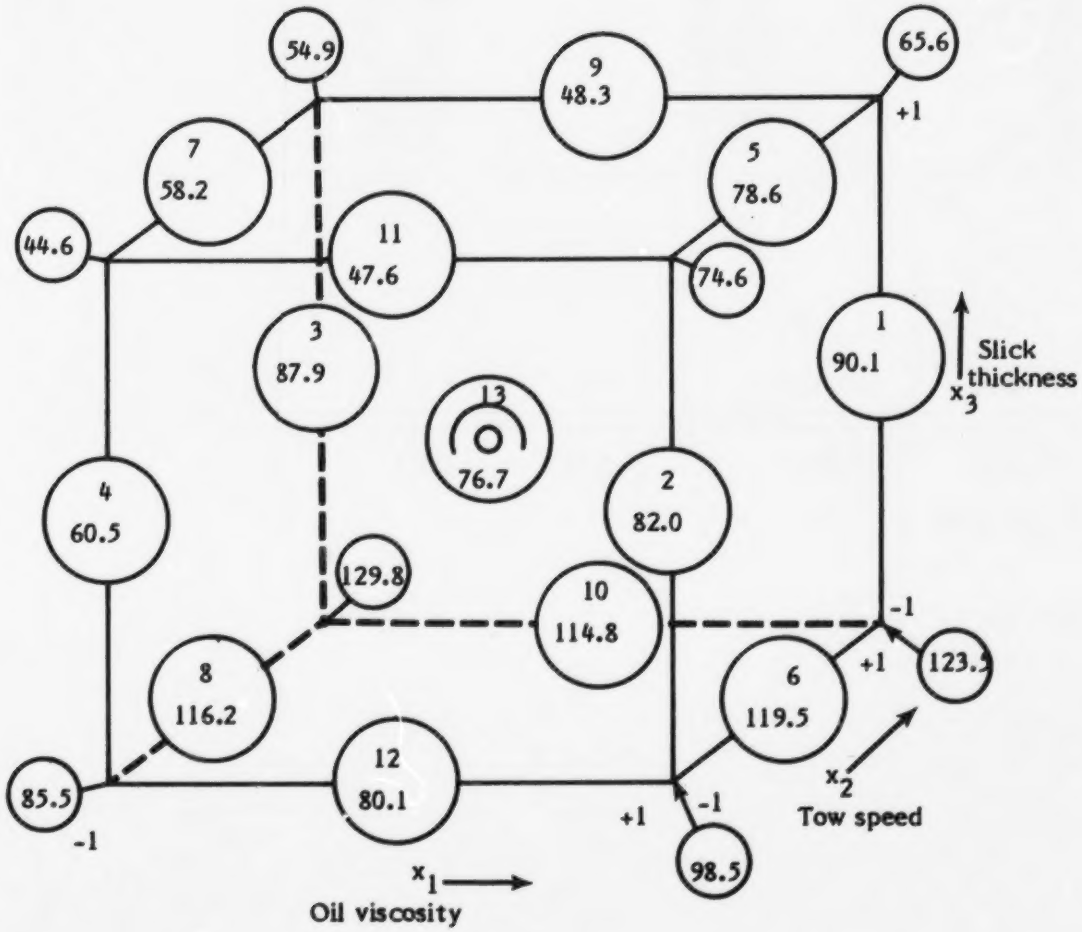

54.9
9
48.3
65.6
+1
7
58.2
5
78.6
44.6
11
47.6
74.6
3
87.9
1
90.1
Slick thickness
x_3
13
76.7
4
60.5
2
82.0
129.8
10
114.8
-1
8
116.2
6
119.5
+1
123.5
12
80.1
85.5
-1
+1
-1
x_2
Tow speed
98.5
x_1
Oil viscosity

FIGURE E-4. CALM SEAS - THROUGHPUT EFFICIENCY (%)
BOX BEHNKEN DIAGRAM.

CALM SEAS - THROUGHPUT EFFICIENCY (%)

```
Y-Data       BOX BEHNKEN DESIGN MATRIX FOR 3 VARIABLES

  95.100      *      *      *      1      1      0
  86.800      *      *      *      1     -1      0
  83.100      *      *      *     -1      1      0
  55.500      *      *      *     -1     -1      0
  66.900      *      *      *      1      0      1
 121.400      *      *      *      1      0     -1
  56.300      *      *      *     -1      0      1
 127.900      *      *      *     -1      0     -1
  55.000      *      *      *      0      1      1
 107.800      *      *      *      0      1     -1
  54.600      *      *      *      0     -1      1
  73.400      *      *      *      0     -1     -1
  84.500      *      *      *      0      0      0
  70.400      *      *      *      0      0      0
  75.200      *      *      *      0      0      0

               COEFFICIENTS TO QUADRATIC EQUATION

Y = B1 + B2*(X1)**2 + B3*(X2)**2 + B4*(X3)**2 + B5*X1 + B6*X2 + B7*X3 +
B8*X1*X2 + B9*X1*X3 + B10*X2*X3

               B( 1)     =      76.700
               B( 2)     =      11.925
               B( 3)     =      -8.500
               B( 4)     =       4.500
               B( 5)     =       5.925
               B( 6)     =       8.838
               B( 7)     =     -24.712
               B( 8)     =      -4.825
               B( 9)     =       4.275
               B(10)     =      -8.500
```

Pt. No.	Actual Y	Approx. Y	Residual
1	95.100	90.062	5.038
2	86.800	82.037	-4.763
3	83.100	87.862	-4.762
4	55.500	60.537	-5.037
5	66.900	78.612	-11.712
6	121.400	119.487	1.913
7	56.300	58.212	-1.912
8	127.900	116.187	11.713
9	55.000	48.325	6.675
10	107.800	114.750	-6.950
11	54.600	47.650	6.950
12	73.400	80.075	-6.675
13	84.500	76.700	7.800
14	70.400	76.700	-6.300
15	75.200	76.700	-1.500

Variance	Std. Dev.	R2	F	D.O.F.1	D.O.F.2
413.099	20.325	0.966	11.415	4	10

$F_{.001} = 11.28$

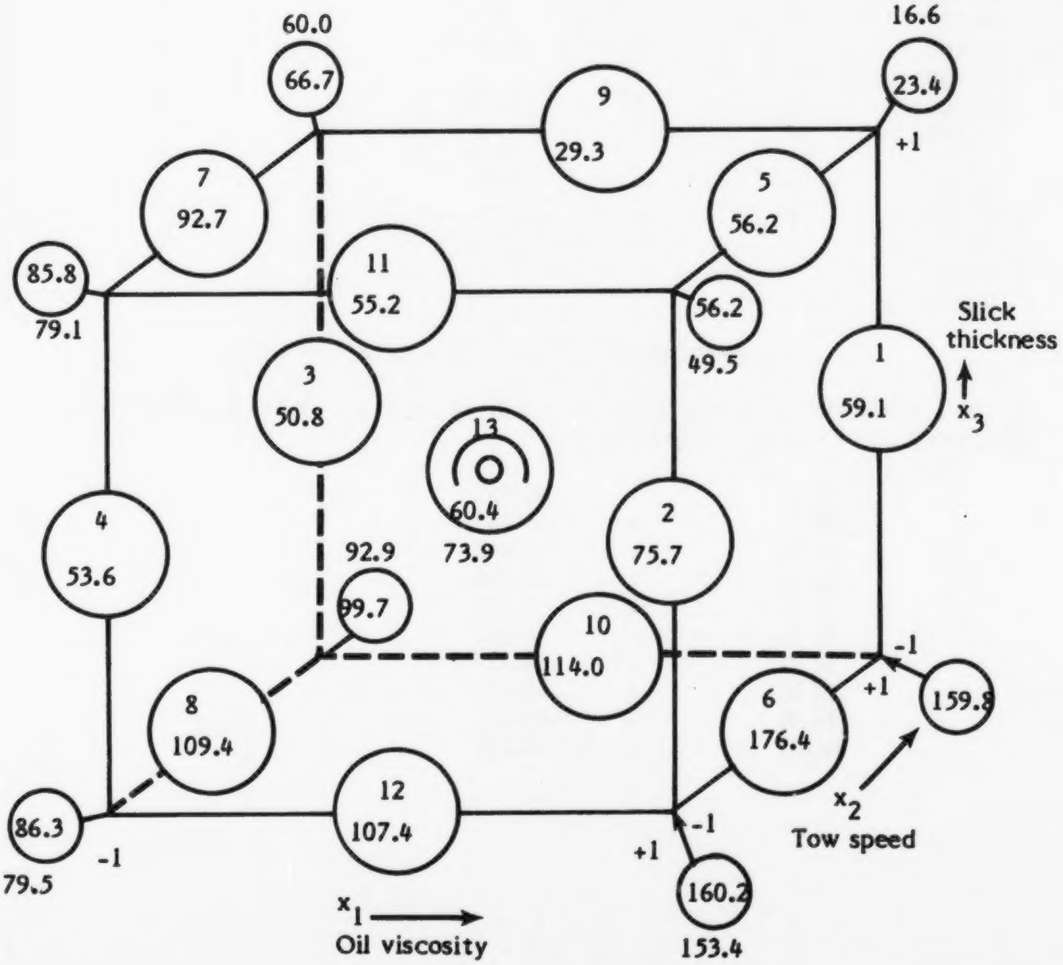

60.0
66.7
16.6
23.4
9
29.3
+1
7
92.7
5
56.2
85.8
79.1
11
55.2
56.2
49.5
Slick thickness
x_3
1
59.1
3
50.8
13
60.4
73.9
4
53.6
2
75.7
92.9
99.7
10
114.0
-1
+1
159.8
6
176.4
8
109.4
12
107.4
86.3
-1
79.5
-1
+1
160.2
153.4
x_2
Tow speed
x_1
Oil viscosity

FIGURE E-5. REGULAR SEAS - THROUGHPUT EFFICIENCY (%) BOX-BEHNKEN DIAGRAM.

REGULAR SEAS - THROUGHPUT EFFICIENCY (%)

```
Y-Data          BOX BEHNKEN DESIGN MATRIX FOR 3 VARIABLES

  40.700     *      *      *      1      1      0
  64.900     *      *      *      1     -1      0
  61.600     *      *      *     -1      1      0
  72.000     *      *      *     -1     -1      0
  64.300     *      *      *      1      0      1
 197.600     *      *      *      1      0     -1
  71.500     *      *      *     -1      0      1
 101.300     *      *      *     -1      0     -1
  39.600     *      *      *      0      1      1
 111.200     *      *      *      0      1     -1
  58.000     *      *      *      0     -1      1
  97.100     *      *      *      0     -1     -1
  33.500     *      *      *      0      0      0
  71.800     *      *      *      0      0      0
  76.000     *      *      *      0      0      0
```

COEFFICIENTS TO QUADRATIC EQUATION

```
Y = B1 + B2*(X1)**2 + B3*(X2)**2 + B4*(X3)**2 + B5*X1 + B6*X2 + B7*X3 +
B8*X1*X2 + B9*X1*X3 + B10*X2*X3

        B( 1)       =     60.433
        B( 2)       =     15.783
        B( 3)       =    -16.417
        B( 4)       =     32.500
        B( 5)       =      7.637
        B( 6)       =     -4.862
        B( 7)       =    -34.225
        B( 8)       =     -3.450
        B( 9)       =    -25.875
        B(10)       =     -8.125
```

Pt. No.	Actual Y	Approx. Y	Residual
1	40.700	59.125	-18.425
2	64.900	75.750	-10.850
3	61.600	50.750	10.850
4	72.000	53.575	18.425
5	64.300	56.213	8.087
6	197.600	176.413	21.187
7	71.500	92.688	-21.188
8	101.300	109.388	-8.088
9	39.600	29.262	10.338
10	111.200	113.963	-2.763
11	58.000	55.263	2.762
12	97.100	107.438	-10.338
13	33.500	60.433	-26.933
14	71.800	60.433	11.367
15	76.000	60.433	15.567

Variance	Std. Dev.	R2	F	D.O.F.1	D.O.F.2
1098.250	33.140	0.857	2.395	4	10

$F_{.05} = 3.48$

REGULAR SEAS - THROUGHPUT EFFICIENCY (%)

Y-Data	BOX BEHNKEN DESIGN MATRIX FOR 3 VARIABLES					
40.700	*	*	*	1	1	0
64.900	*	*	*	1	-1	0
61.600	*	*	*	-1	1	0
72.000	*	*	*	-1	-1	0
64.300	*	*	*	1	0	1
197.600	*	*	*	1	0	-1
71.500	*	*	*	-1	0	1
101.300	*	*	*	-1	0	-1
39.600	*	*	*	0	1	1
111.200	*	*	*	0	1	-1
58.000	*	*	*	0	-1	1
97.100	*	*	*	0	-1	-1
71.800	*	*	*	0	0	0
76.000	*	*	*	0	0	0

COEFFICIENTS TO QUADRATIC EQUATION

Y = B1 + B2*(X1)**2 + B3*(X2)**2 + B4*(X3)**2 + B5*X1 + B6*X2 + B7*X3 + B8*X1*X2 + B9*X1*X3 + B10*X2*X3

B(1) = 73.900
B(2) = 9.050
B(3) = -23.150
B(4) = 25.725
B(5) = 7.637
B(6) = -4.862
B(7) = -34.225
B(8) = -3.450
B(9) = -25.875
B(10) = -8.125

Pt. No.	Actual Y	Approx. Y	Residual
1	40.700	59.125	-18.425
2	64.900	75.749	-10.849
3	61.600	50.751	10.849
4	72.000	53.575	18.425
5	64.300	56.212	8.088
6	197.600	176.412	21.188
7	71.500	92.688	-21.188
8	101.300	109.388	-8.088
9	39.600	29.263	10.337
10	111.200	113.963	-2.763
11	58.000	55.237	2.763
12	97.100	107.437	-10.337
13	71.800	73.900	-2.100
14	76.000	73.900	2.100

Variance	Std. Dev.	R2	F	D.O.F.1	D.O.F.2
167.758		0.892	2.484	3	10

$F_{.05} = 3.71$

$F_{.01} = 2.73$

S.D. = 12.952

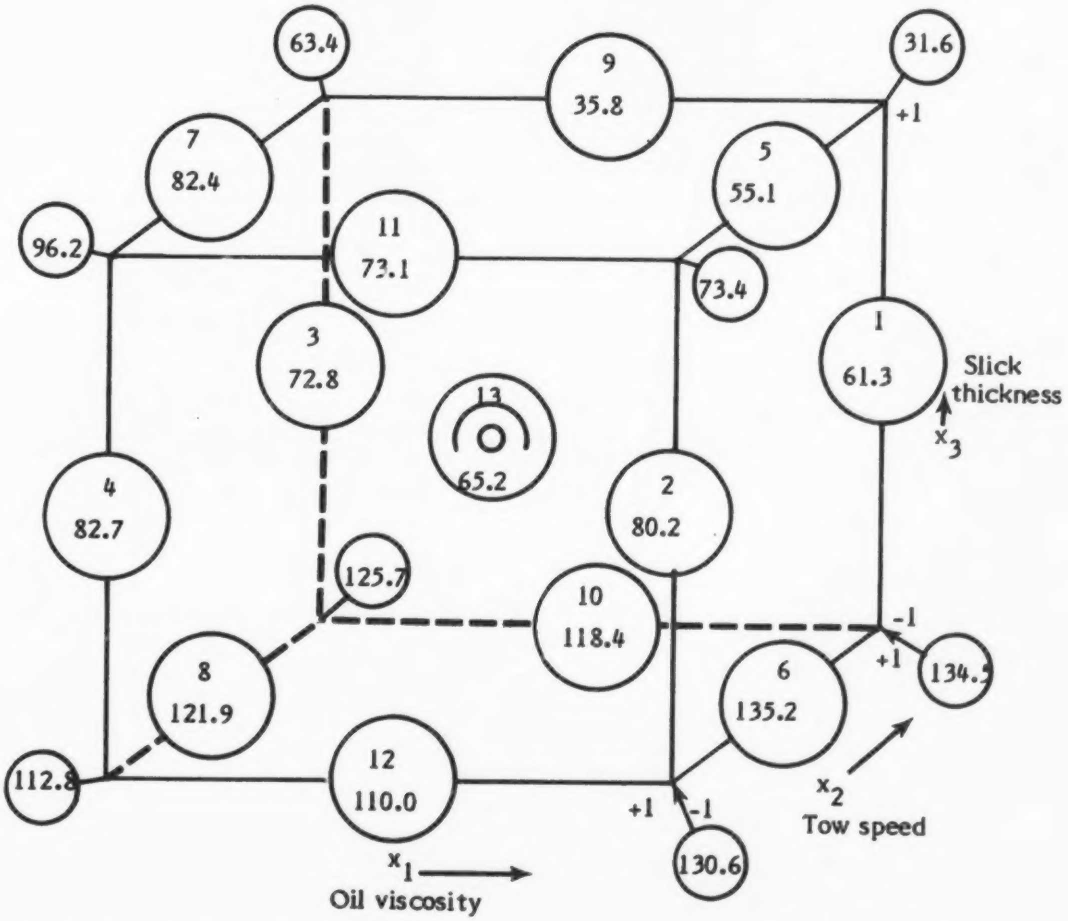

63.4
9
35.8
31.6
+1
7
82.4
5
55.1
96.2
11
73.1
73.4
3
72.8
1
61.3
Slick thickness
x_3
13
65.2
4
82.7
2
80.2
125.7
10
118.4
-1
+1
134.5
8
121.9
6
135.2
112.8
12
110.0
+1
-1
130.6
x_2
Tow speed
x_1
Oil viscosity

FIGURE E-6. HARBOR CHOP - THROUGHPUT EFFICIENCY (%) BOX BEHNKEN DIAGRAM.

HARBOR CHOP - THROUGHPUT EFFICIENCY (%)

```
Y-Data      BOX BEHNKEN DESIGN MATRIX FOR 3 VARIABLES

 64.900     *     *     *      1      1      0
 80.600     *     *     *      1     -1      0
 72.400     *     *     *     -1      1      0
 79.100     *     *     *     -1     -1      0
 45.500     *     *     *      1      0      1
140.800     *     *     *      1      0     -1
 76.800     *     *     *     -1      0      1
131.500     *     *     *     -1      0     -1
 41.800     *     *     *      0      1      1
109.200     *     *     *      0      1     -1
 82.300     *     *     *      0     -1      1
104.000     *     *     *      0     -1     -1
 68.400     *     *     *      0      0      0
 61.700     *     *     *      0      0      0
 65.500     *     *     *      0      0      0
```

COEFFICIENTS TO QUADRATIC EQUATION

```
Y = B1 + B2*(X1)**2 + B3*(X2)**2 + B4*(X3)**2 + B5*X1 + B6*X2 + B7*X3 +
B8*X1*X2 + B9*X1*X3 + B10*X2*X3

            B( 1)       =      65.200
            B( 2)       =      11.688
            B( 3)       =      -2.637
            B( 4)       =      21.763
            B( 5)       =      -3.500
            B( 6)       =      -7.213
            B( 7)       =     -29.887
            B( 8)       =      -2.250
            B( 9)       =     -10.150
            B(10)       =     -11.425
```

Pt. No.	Actual Y	Approx. Y	Residual
1	64.900	61.287	3.613
2	80.600	80.213	0.387
3	72.400	72.787	-0.387
4	79.100	82.713	-3.613
5	45.500	55.113	-9.613
6	140.800	135.188	5.612
7	76.800	82.413	-5.613
8	131.500	121.888	9.612
9	41.800	35.800	6.000
10	109.200	118.425	-9.225
11	82.300	73.075	9.225
12	104.000	110.000	-6.000
13	68.400	65.200	3.200
14	61.700	65.200	-3.500
15	65.500	65.200	0.300

Variance	Std. Dev.	R2	F	D.O.F.1	D.O.F.2
38.499	6.205	0.953	8.038	4	10

$F_{.005} = 7.34$

CALM SEAS - RECOVERY EFFICIENCY (%)

Y-Data	BOX BEHNKEN DESIGN MATRIX FOR 3 VARIABLES					
52.000	*	*	*	1	1	0
75.000	*	*	*	1	-1	0
34.000	*	*	*	-1	1	0
58.000	*	*	*	-1	-1	0
61.000	*	*	*	1	0	1
36.000	*	*	*	1	0	-1
47.000	*	*	*	-1	0	1
35.000	*	*	*	-1	0	-1
54.000	*	*	*	0	1	1
44.000	*	*	*	0	1	-1
90.000	*	*	*	0	-1	1
52.000	*	*	*	0	-1	-1
57.000	*	*	*	0	0	0
55.000	*	*	*	0	0	0
54.000	*	*	*	0	0	0

COEFFICIENTS TO QUADRATIC EQUATION

Y = B1 + B2*(X1)**2 + B3*(X2)**2 + B4*(X3)**2 + B5*X1 + B6*X2 + B7*X3 + B8*X1*X2 + B9*X1*X3 + B10*X2*X3

B(1) = 55.333
B(2) = -7.917
B(3) = 7.333
B(4) = -2.667
B(5) = 6.250
B(6) = -11.375
B(7) = 10.625
B(8) = 0.250
B(9) = 3.250
B(10) = -7.000

Pt. No.	Actual Y	Approx. Y	Residual
1	52.000	49.875	2.125
2	75.000	72.125	2.875
3	34.000	36.875	-2.875
4	58.000	60.125	-2.125
5	61.000	64.875	-3.875
6	36.000	37.125	-1.125
7	47.000	45.875	1.125
8	35.000	31.125	3.875
9	54.000	52.250	1.750
10	44.000	45.000	-1.000
11	90.000	89.000	1.000
12	52.000	53.750	-1.750
13	57.000	55.333	1.667
14	55.000	55.333	-0.333
15	54.000	55.333	1.333

Variance	Std. Dev.	R2	F	D.O.F.1	D.O.F.2
5.065	2.251	0.977	16.812	6	10

$F_{(.001)} = 11.28$

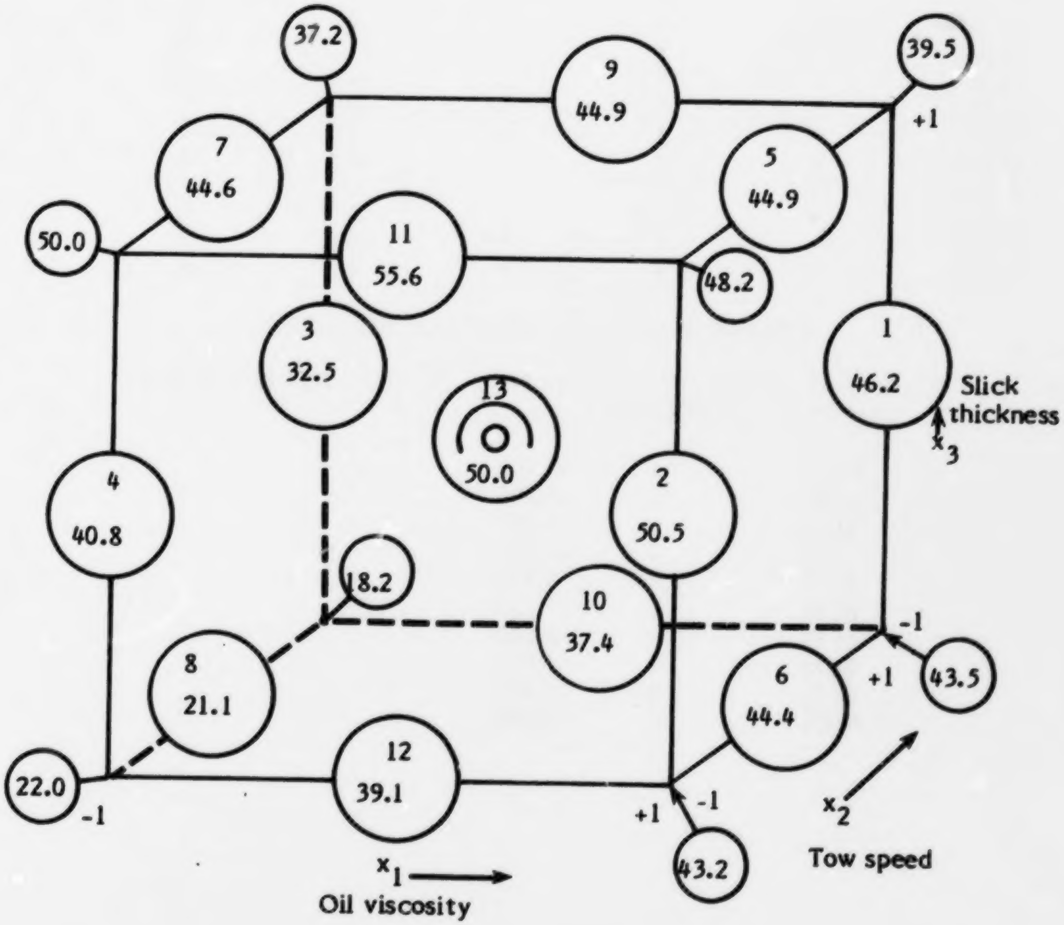

37.2
9
44.9
39.5
+1
7
44.6
5
44.9
50.0
11
55.6
48.2
3
32.5
1
46.2
Slick thickness
x_3
13
50.0
4
40.8
2
50.5
18.2
10
37.4
-1
8
21.1
6
44.4
+1
43.5
12
39.1
22.0
-1
+1
-1
43.2
x_2
Tow speed
x_1
Oil viscosity

FIGURE E-7. HARBOR CHOP - RECOVERY EFFICIENCY (%) BOX BEHNKEN DIAGRAM.

HARBOR CHOP - RECOVERY EFFICIENCY (%)

Y-Data	BOX BEHNKEN DESIGN MATRIX FOR 3 VARIABLES					
46.000	*	*	*	1	1	0
47.000	*	*	*	1	-1	0
36.000	*	*	*	-1	1	0
41.000	*	*	*	-1	-1	0
47.000	*	*	*	1	0	1
46.000	*	*	*	1	0	-1
43.000	*	*	*	-1	0	1
19.000	*	*	*	-1	0	-1
43.000	*	*	*	0	1	1
36.000	*	*	*	0	1	-1
57.000	*	*	*	0	-1	1
41.000	*	*	*	0	-1	-1
54.000	*	*	*	0	0	0
47.000	*	*	*	0	0	0
49.000	*	*	*	0	0	0

COEFFICIENTS TO QUADRATIC EQUATION

```
Y = B1 + B2*(X1)**2 + B3*(X2)**2 + B4*(X3)**2 + B5*X1 + B6*X2 + B7*X3 +
B8*X1*X2 + B9*X1*X3 + B10*X2*X3
```

```
B( 1)   =   50.000
B( 2)   =   -6.500
B( 3)   =   -1.000
B( 4)   =   -4.750
B( 5)   =    5.875
B( 6)   =   -3.125
B( 7)   =    6.000
B( 8)   =    1.000
B( 9)   =   -5.750
B(10)   =   -2.250
```

Pt. No.	Actual Y	Approx. Y	Residual
1	46.000	46.250	-0.250
2	47.000	50.500	-3.500
3	36.000	32.500	3.500
4	41.000	40.750	0.250
5	47.000	44.875	2.125
6	46.000	44.375	1.625
7	43.000	44.625	-1.625
8	19.000	21.125	-2.125
9	43.000	44.875	-1.875
10	36.000	37.375	-1.375
11	57.000	55.625	1.375
12	41.000	39.125	-1.875
13	54.000	50.000	4.000
14	47.000	50.000	-3.000
15	49.000	50.000	-1.000

Variance	Std. Dev.	R2	F	D.O.F.1	D.O.F.2
0.411	2.326	0.931	5.397	4	10

$F_{(.05)} = 3.48$

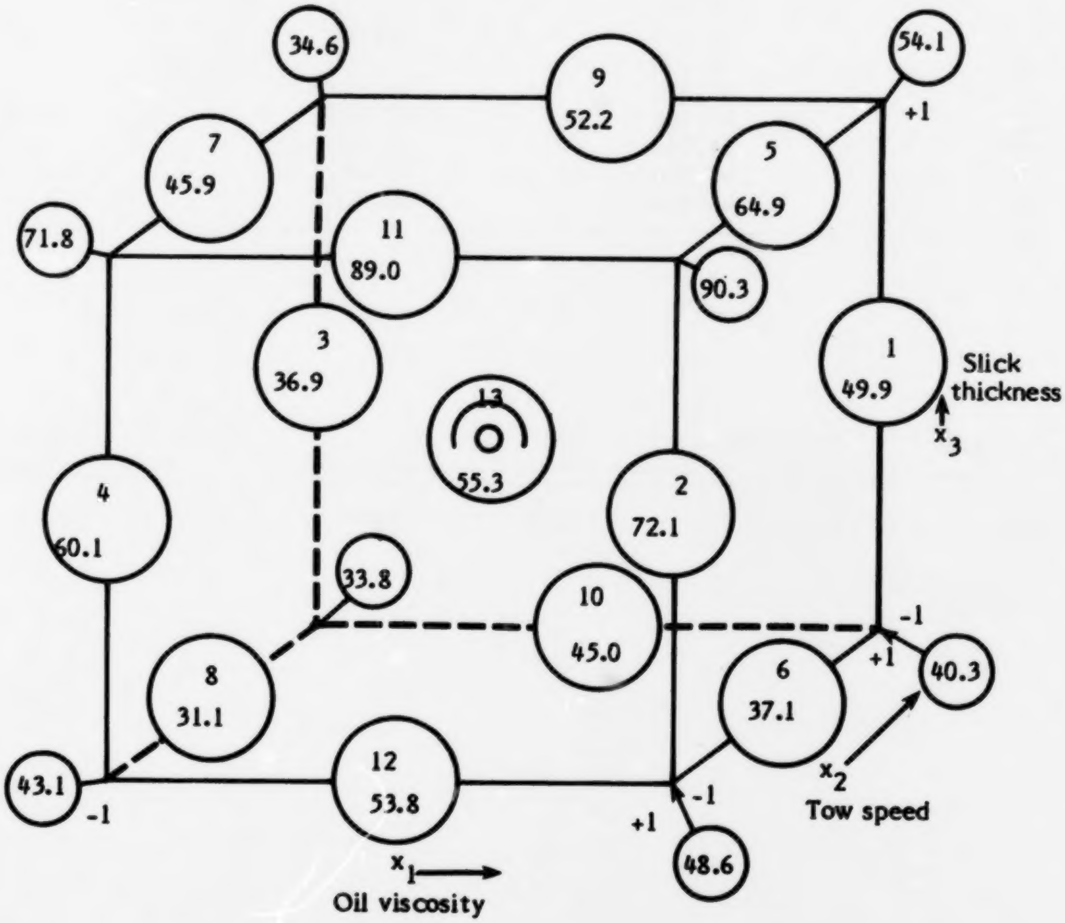

34.6
9
52.2
54.1
+1
7
45.9
5
64.9
71.8
11
89.0
90.3
3
36.9
1
49.9
Slick thickness
x_3
13
55.3
4
60.1
2
72.1
33.8
10
45.0
-1
+1
40.3
8
31.1
6
37.1
12
53.8
43.1
-1
+1
-1
x_2
Tow speed
48.6
x_1
Oil viscosity

FIGURE E-8. CALM SEAS - RECOVERY EFFICIENCY (%)
BOX BEHNKEN DIAGRAM.

REGULAR SEAS - RECOVERY EFFICIENCY (%)

```
Y-Data        BOX BEHNKEN DESIGN MATRIX FOR 3 VARIABLES

 47.000      *       *       *       1       1       0
 41.000      *       *       *       1      -1       0
 32.000      *       *       *      -1       1       0
 31.000      *       *       *      -1      -1       0
 72.000      *       *       *       1       0       1
 44.000      *       *       *       1       0      -1
 37.000      *       *       *      -1       0       1
 35.000      *       *       *      -1       0      -1
 41.000      *       *       *       0       1       1
 43.000      *       *       *       0       1      -1
 75.000      *       *       *       0      -1       1
 19.000      *       *       *       0      -1      -1
 35.000      *       *       *       0       0       0
 45.000      *       *       *       0       0       0
 48.000      *       *       *       0       0       0
```

COEFFICIENTS TO QUADRATIC EQUATION

```
Y = B1 + B2*(X1)**2 + B3*(X2)**2 + B4*(X3)**2 + B5*X1 + B6*X2 + B7*X3 +
B8*X1*X2 + B9*X1*X3 + B10*X2*X3

              B( 1)      =      42.667
              B( 2)      =      -1.208
              B( 3)      =      -3.708
              B( 4)      =       5.542
              B( 5)      =       8.625
              B( 6)      =      -0.375
              B( 7)      =      10.500
              B( 8)      =       1.250
              B( 9)      =       6.500
              B(10)      =     -14.500
```

Pt. No.	Actual Y	Approx. Y	Residual
1	47.000	47.250	-0.250
2	41.000	45.500	-4.500
3	32.000	27.500	4.500
4	31.000	30.750	0.250
5	72.000	72.625	0.625
6	44.000	38.625	5.375
7	37.000	42.375	-5.375
8	35.000	34.375	0.625
9	41.000	40.125	0.875
10	43.000	48.125	-5.125
11	75.000	69.875	5.125
12	19.000	19.875	-0.875
13	35.000	42.667	-7.667
14	45.000	42.667	2.333
15	48.000	42.667	5.333

Variance	Std. Dev.	R2	F	D.O.F.1	D.O.F.2
17.565	4.191	0.916	4.356	4	10

$F_{(.05)} = 3.48$

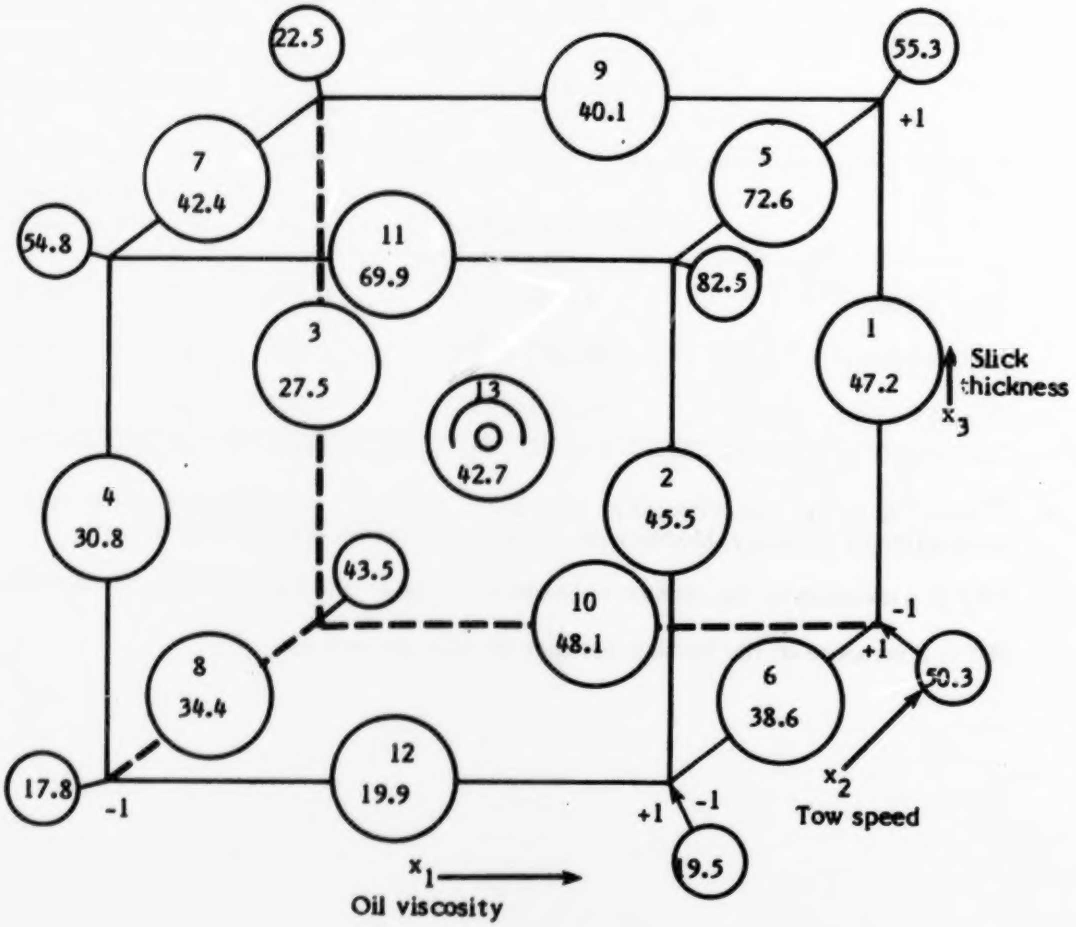

22.5
9
40.1
55.3
+1
7
42.4
5
72.6
54.8
11
69.9
82.5
3
27.5
13
42.7
1
47.2
Slick thickness
x_3
4
30.8
2
45.5
43.5
10
48.1
-1
+1
50.3
8
34.4
6
38.6
12
19.9
17.8
-1
+1
-1
x_2
Tow speed
19.5
x_1
Oil viscosity

FIGURE E-9. REGULAR SEAS - RECOVERY EFFICIENCY (%) BOX BEHNKEN DIAGRAM.

APPENDIX F

TEST OIL PROPERTIES

OHMSETT test oils used for the USCG ZRV Oil Skimmer Test Program.

TABLE F-1. SPECIFICATIONS OF TEST FLUIDS USED.

	Viscosity (cSt)	Specific Gravity dynes/cm	IFT* dynes/cm	SFT
	Water Temperature	------	with distilled water at 25°C	
Circo X Heavy[a]	950 @ 20°C	0.938	8.8	34.6
Circo Medium	350 @ 19.3°C	0.928	6.5	33.3
Circo 4X Light	31 @ 18.3°C	0.908	2.7	31.4

[a] Circo is a Sun Oil Company, Inc. brand name of a naphthenic base oil. The designation of X Heavy, Medium, or 4X Light stipulates the grade of oil.

*IFT is a measure of the tension between an oil layer and OHMSETT tank water layer.

SFT is a measure of the tension between an oil layer and air.

APPENDIX G

HYDROCARBON VAPOR DETECTION TESTS

ZRV VAPOR CONCENTRATIONS

Vapor concentrations were taken on both sides inside the wringer compartment during pickup of CIRCO 4X light oil on 2 October 1979. Air temperature was 65°F.

Test positions were:

#1 - middle of wringer, stbd side

#2 - center of stbd side

#3 - fwd and low on stbd side

#4 - Aft and high on port side

#5 - center of port side

#6 - middle of wringer, port side

The test readings show very low vapor concentrations within the compartment under the test conditions. The maximum reading was only 4% of the lower explosive limit which is about 1% concentration of hydrocarbons. Therefore, no explosive or fire risk was present. This is not to say that a hazard would not exist under other conditions. The limiting conditions for safe operation which were sought through this experiment were not determined.

TABLE G-1. USCG ZRV SKIMMER, EXPLOSION LIMIT TESTING

	Sample Location and Distance from Oil						
Test	1 6"	2 12"	3 12"	4 12"	5 12"	6 12"	Remarks
Test #1	140 ppm						
		140 ppm	275 ppm	110 ppm	90 ppm	150 ppm	Sample taken with belt speed of 1 knot, with skimmer not moving.
		3% of LEL 210 ppm*	200 ppm*	120 ppm	150 ppm	210 ppm	*Probably out of oil.
Test #2	140 ppm	150 ppm	120 ppm	25 ppm	50 ppm	75 ppm	Sample taken with belt speed of 2 knots, with skimmer moving.
		110 ppm	150 ppm	50 ppm	55 ppm	60 ppm	

2% of LEL = 140 ppm
3% of LEL = 210 ppm
4% of LEL = 280 ppm

Test #3	Sample of oil used in Tests #1, 2 was put in a quart jar ½ full, shaken, and then a sample was taken 2 minutes later. Reading was 100 ppm.
Test #4	Reading of oil at water level was 50 ppm.
Test #5	Reading of oil at rear of skimmer between the belts was 120 ppm (very little oil dumped).
Test #6	Same as #5, 110 ppm.
Test #7	Reading taken at Fwd. belt area (bow) on the stbd side, 100 ppm).
Test #8	Port engine room underway, light oil, 50 ppm.

FLAMMABILITY CHART shows why care must be taken to keep hydrocarbon levels below two percent of volume. Note explosive region in triangle.

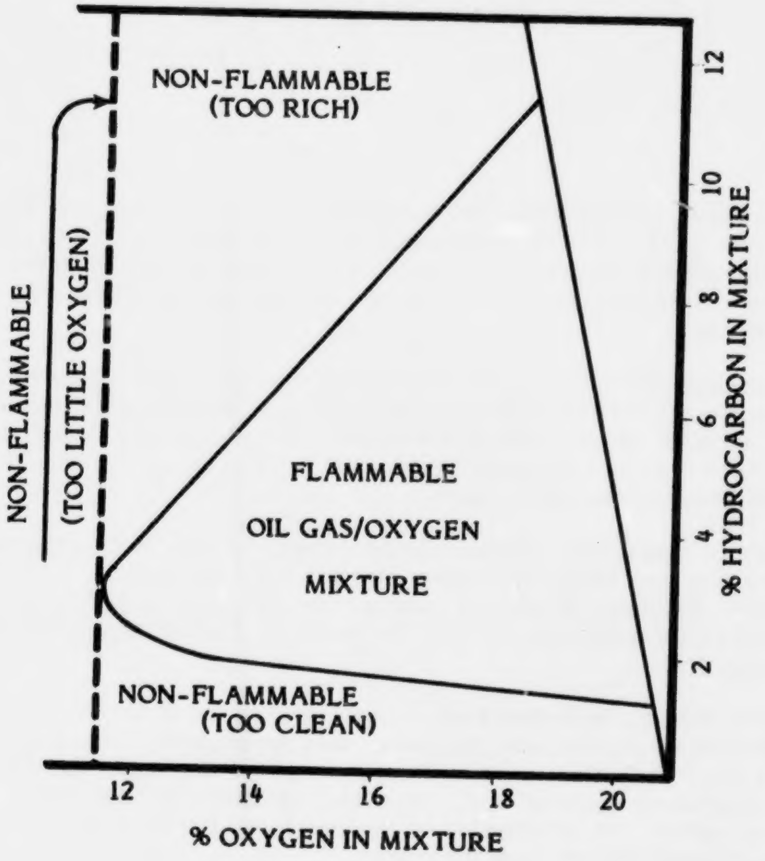


FIGURE G-1. HYDROCARBON FLAMMABILITY CHART.

APPENDIX H

ZRV CONCENTRATION BOOMS

INTRODUCTION

Background

All skimmers, including the ZRV skimmer, are limited in their ability to recover oil slicks by the width of their entrance. Many operators have circumvented this limitation by deploying oil-diverting booms in a "V" configuration immediately ahead of the skimmer to concentrate the oncoming slick from some width greater than the skimmer's entrance.

Conventional flat plate booms frequently used for this purpose have considerably extended the effectiveness of clean-up operations, affording increases in encounter width of as much as ten- and twenty-fold. These type booms are generally not useful beyond 1½ knots, consequently rendering them inappropriate for the ZRV skimmer at its designed operating range.

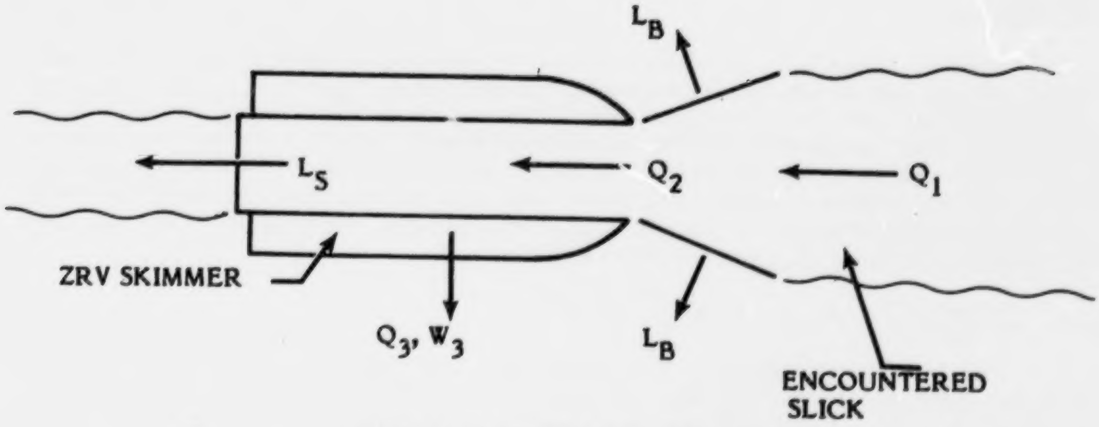
Because of substantial benefits derived from the use of concentration booms, advanced concepts are being considered for the ZRV skimmer. Two fast-current diversion boom concepts, developed and proven in other R&D programs, showed particular promise for adaptation to the ZRV skimmer. Hence, they were tested under the present program.

The two devices, described fully in the text, rely on a system of fluid jets; one employs a system of air-jets and the other uses water-jets. The following section reviews some basic definitions used to describe the flow and performance characteristics of skimmer/boom systems and discusses important factors that make up an efficient boom system. A description of the details of the OHMSETT test conditions and results, with analysis, conclude the report.

Flow and Performance Definitions

Concentration booms used in the ZRV skimmer tests have the general configuration shown in Figure H-1. The waterline planform depicts the approximate paths of oil flow (Q) and areas where oil losses may occur (L). All quantities have units of volume because that is what is measured during the test. However, they can also be thought of as having units of flow rate.

As shown in Figure H-1, the oncoming slick, denoted by Q_1, approaches the skimmer and is progressively narrowed and thickened by the boom. Oil loss, L_B, which may occur along the boom (or at its juncture with the skimmer), reduces the volume passing into the skimmer's entrance, Q_2. If there are no losses, then clearly Q_1 equals Q_2. Oil from the boom passes into the skimmer, where it is recovered as a mixture of


L_B
L_S
Q_2
Q_1
ZRV SKIMMER
Q_3, W_3
L_B
ENCOUNTERED SLICK

Q_1 = INITIAL SLICK VOLUME, OIL

Q_2 = SKIMMER ENTRANCE VOLUME, OIL

Q_3 = SKIMMER RECOVERY VOLUME, OIL

W_3 = SKIMMER RECOVERY VOLUME, WATER

L_B = BOOM OIL LOSS VOLUME

L_S = SKIMMER OIL LOSS VOLUME

E_S = $(Q_3/Q_2)\ 100$ = INDEPENDENT SKIMMER THROUGHPUT EFFICIENCY

$E_{S/B}$ = $(Q_3/Q_1)\ 100$ = SKIMMER/BOOM THROUGHPUT EFFICIENCY

E_B = $E_{S/B}/E_S$ = BOOM DIVERSION EFFICIENCY

E_R = $((Q_3/(Q_3 + W_3))\ 100$ = OIL RECOVERY EFFICIENCY

FIGURE H-1. EFFICIENCY DEFINITIONS FOR ZRV SKIMMER/BOOM TESTS.

oil and water, Q_3 and W_3, respectively. Oil not recovered, L_S, is lost in the wake of the skimmer.

Specific ratios (i.e., efficiencies) used to compare skimmer/boom performance under varying sets of operating conditions, are defined in Figure H-1. Two frequently used definitions are the throughput efficiency, which is the percent fraction of oil recovered to oil distributed, and the recovery efficiency, which is the percent fraction of oil recovered to water recovered. A third type of efficiency of a less conventional form is also defined - boom efficiency. It is based on the idea that the total skimmer/boom throughput efficiency, $E_{S/B}$, is made up of the product of the skimmer throughput efficiency, E_S, and the boom efficiency, E_B.

That is, $E_{S/B} = E_S \times E_B$(1)

The boom's efficiency is determined by measuring the efficiency of the ZRV skimmer with the boom and then dividing by the efficiency of the ZRV skimmer without the boom. It follows that if a boom is 100% effective ($E_B = 1$), the skimmer will recover the slick as if no booms were present.

The concept of boom efficiency is not quite as simple as it may appear. For example, a boom that diverts oil into the ZRV skimmer without loss may be very inefficient. This is because of the complex influence the boom can have on the slick thickness and, thus, the skimmer's performance.

For the ZRV skimmer, an efficient concentration boom must provide two key functions:

(1) Effective diversion of the oncoming slick into the entrance of the skimmer, i.e., minimum loss; and

(2) Maintenance of a uniform slick thickness distribution across the width of the ZRV skimmer entrance to provide for efficient belt saturation.

Figure H-2 illustrates two extreme types of slick distributions; a uniform slick distribution, t_o, providing good performance, and a distorted slick distribution, t, causing degraded skimmer performance.

While the importance of slick distribution can be understood qualitatively, measuring the extent to which it occurs during testing is not presently feasible. Nevertheless, some insight about slick distribution may be reckoned from the measured skimmer efficiency. This will be discussed in a later section.

An alternative approach is to use an empirical parameter that describes the relative ability of the boom to maintain a uniform slick. The parameter, called the slick thickness distribution factor, δ, serves to modify the equation that ordinarily is used to indicate boom diversion efficiency. This new equation is:

$$E_B = Q_2/Q_1(\delta)$$

Clearly, efficient concentration booms would have values of δ approaching unity and the less efficient booms have values approaching zero.

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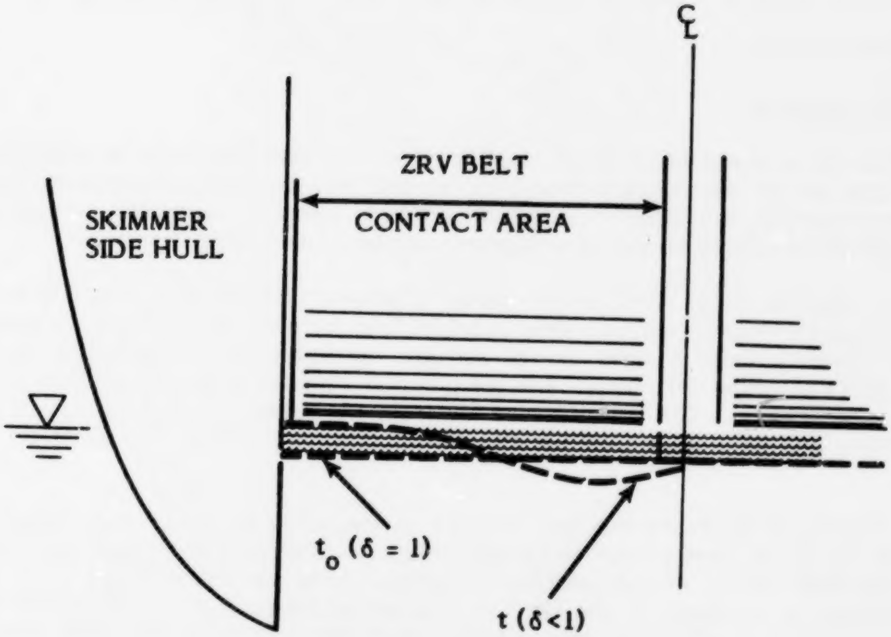
(1) Notation for the air-jet boom and water-jet boom throughput efficiency are $(E_{S/B})_A$ and $(E_{S/B})_W$, respectively. Similar notation is used for recovery efficiency.



SECTION DOWNSTREAM OF CONCENTRATION BOOMS

$t_o(\delta=1)$	OPTIMUM PERFORMANCE BEST SLICK THICKNESS DISTRIBUTION. RESULTS IN UNIFORM SATURATION OF ZRV BELT.
$t\,(\delta<1)$	DEGRADED PERFORMANCE POOR SLICK THICKNESS DISTRIBUTION CAUSED BY INFLUENCE OF CONCENTRATION BOOMS. RESULTS IN LOCALIZED OVER-SATURATION (INBOARD) AND UNDER-SATURATION (OUTBOARD) OF ZRV BELT (ARBITRARY DISTRIBUTION SHOWN)

FIGURE H-2. SLICK THICKNESS DISTRIBUTION APPROACHING ZRV SKIMMER.

One way to determine δ indirectly is to divide E_B by the ratio of Q_2/Q_1. This would, however, entail a method of measuring Q_2 or L_B. Obviously, this is no simple undertaking and, consequently, is not accomplished in the present program. However, a case where the value of δ can be determined with ease is when $Q_1 = Q_2$ ($L_B = 0$).

BOOM DESCRIPTIONS

Air-jet Boom - General

The air-jet concentration boom used for the ZRV skimmer tests is a modified version of the air-jet diversionary boom developed for stationary service in fast-moving currents where the deployment of conventional booms is precluded. A detailed account of the diversionary boom's development can be found in Reference 3.

In its original form, the air-jet boom is about 33 feet long and 2 feet in diameter. The major components include two 14½ feet long inflatable fabric cylinders (or ducts) extending from a rigid center section that supplies low-pressure air by means of a float-mounted jet pump. The jet pump is supplied by a shore-based high-pressure air compressor. The low-pressure air from the jet pump goes to inflate the fabric cylinders and to provide flow for the continuous nozzle along the front of the boom.

The nozzle, oriented to the free surface as indicated in Figure H-3, directs a high-velocity jet of air flow at the air/water interface along the length of the boom. The resulting shear stress at the interface induces a local surface current; when the boom is deployed at an angle to the flow, a thin oncoming oil slick is deflected and transported by this current across the surface, apart from the underlying bulk flow of clean water. When the boom encounters waves, the induced surface current is generally undiminished because the inflatable sections are compliant; thus they conform to the wave contours and maintain the necessary air-jet orientation.

Air-jet Boom - Test Set-up

The air-jet boom, as adapted to the ZRV skimmer, is shown in Figure H-4. The photograph shows the starboard inflatable boom section and a portion of the port inflatable boom section which was taken from the original air-jet boom's left and right sections, respectively. Using the original jet pump as an air supply, flexible ducts (not shown) lead low-pressure air to the transition ducts (shown), which connect to the inflatable sections. The flow characteristics for the compressor and jet pump are given in Figure H-5.

The jet pump was secured with ropes to the main bridge at a point in line with the skimmer's centerline. The high-pressure compressor supplying the jet pump was carried on the auxiliary bridge. The high-pressure hose connecting the two can be seen in Figure H-4, running from top left to bottom right. Overhead ropes were used to support the flexible duct and transition duct to prevent them from dragging in the water.

Support to withstand drag forces on the boom and maintain the prescribed boom angle was provided by port and starboard cables attached to each side hull of the

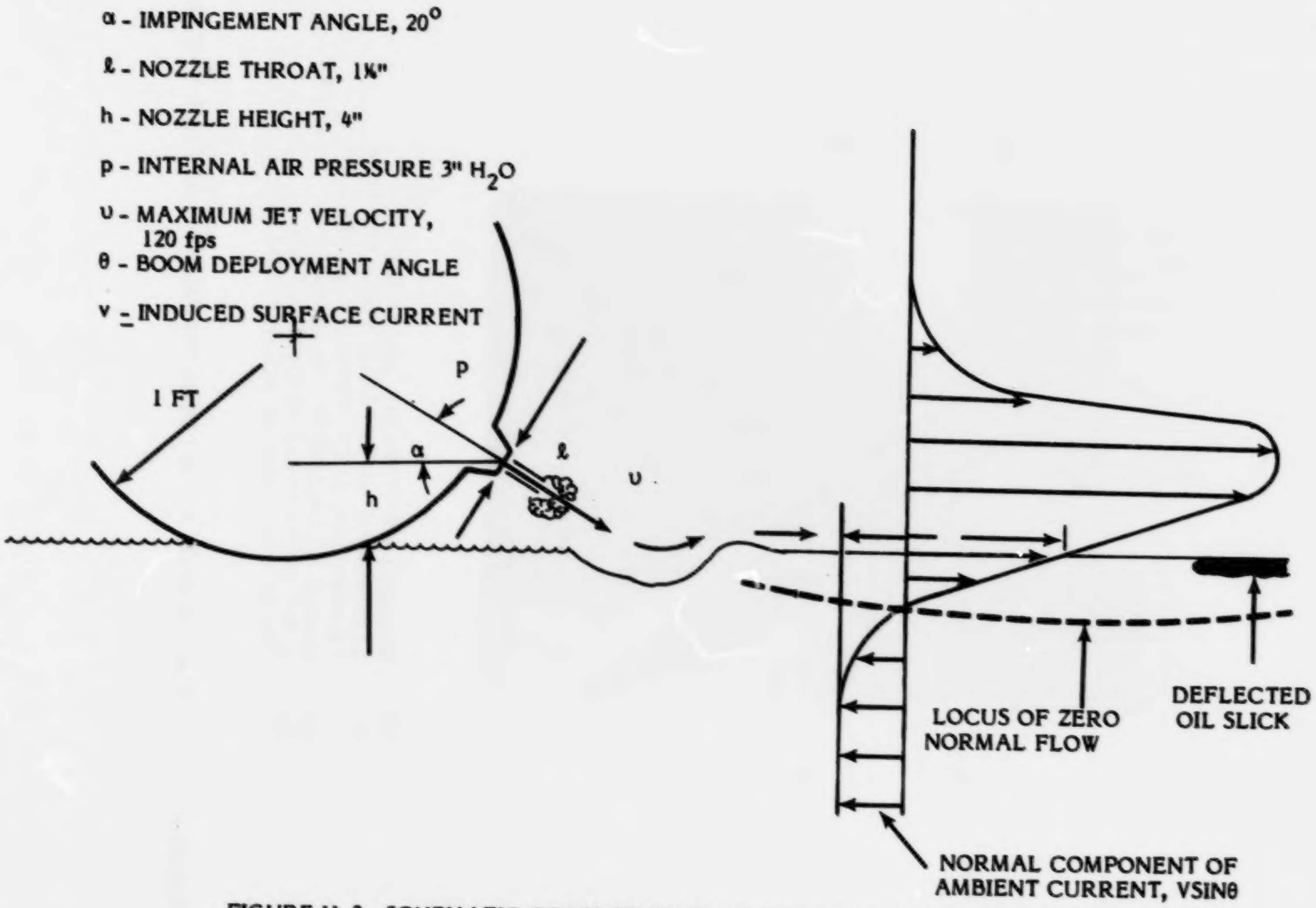
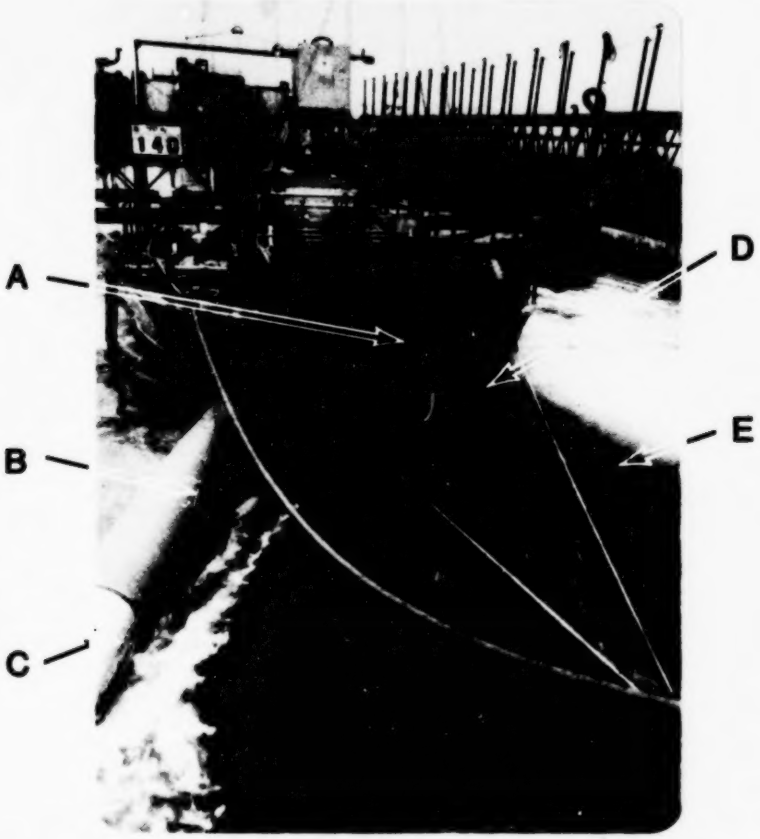

α - IMPINGEMENT ANGLE, 20°
ℓ - NOZZLE THROAT, 1⅛"
h - NOZZLE HEIGHT, 4"
p - INTERNAL AIR PRESSURE 3" H_2O
υ - MAXIMUM JET VELOCITY, 120 fps
θ - BOOM DEPLOYMENT ANGLE
v ± INDUCED SURFACE CURRENT
1 FT
p
α
h
ℓ
υ
LOCUS OF ZERO NORMAL FLOW
DEFLECTED OIL SLICK
NORMAL COMPONENT OF AMBIENT CURRENT, VSINθ

FIGURE H-3. SCHEMATIC CROSS SECTION OF THE AIR JET BOOM AND GENERALIZED AIR/WATER INTERFACE VELOCITY PROFILE.



A	SKIMMER CENTERLINE WATERJET
B	STARBOARD INFLATABLE BOOM SECTION
C	TRANSITION DUCT FROM AIR SUPPLY
D	CABLE ATTACHMENT TO SKIMMER
E	PORT INFLATABLE BOOM SECTION (NOTE CONTINUOUS AIR-JET NOZZLE)

FIGURE H-4. ZRV SKIMMER WITH AIR JET BOOMS OPERATING AT FOUR KNOTS.

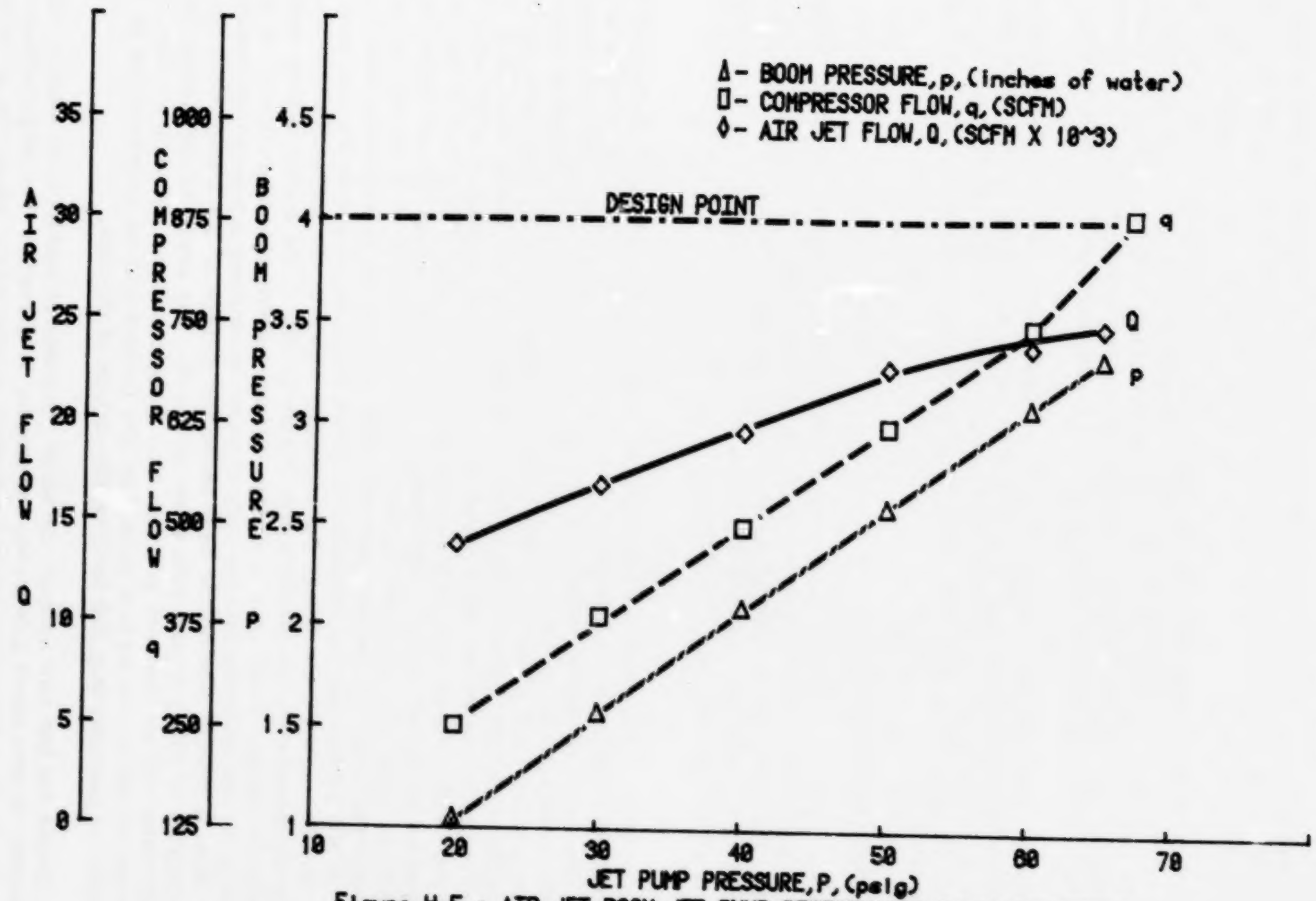


Figure H-5 : AIR JET BOOM JET PUMP PERFORMANCE CHARACTERISTICS skimmer and the main bridge. Constant cable tension is provided by counterweights (175 pounds each), with sufficient travel to compensate for relative motion of the skimmer fore and aft.

An important adjustment for the boom is the height of the cable above the water's surface (1 foot), because it sets the jet impingement angle. Although this is a less than desirable arrangement for a prototype ZRV system, it was considered acceptable for the OHMSETT tests. However, one unfortunate consequence is that the boom must be operated in calm water only, with no capability to perform in waves.

For a prototype boom system engineered specifically for the ZRV skimmer, wave following capabilities could be provided by taking advantage of the air-jet boom inherent insensitivity to waves. Similarly, an air supply system, ducts, rigging, etc., would all be somewhat different from the test set-up, except with respect to the continuous air jet.

Water Jet Oil Herder - General

The water jet system employed in these tests consisted of long, splayed aluminum booms with vertically directed nozzles at the forward end (Figures H-6, H-7, and H-8). The water jet oil herding system was developed by the US EPA at OHMSETT to control oil slicks in fast currents and in waves where conventional booms would fail or cause excess turbulence. The development of the system is described in US EPA reports.[2,3]

The water jets employ the impact of the water stream hitting the water and the rising bubbles from the air it entrains to create a surface current and thus move an oil slick. The force of impact creates a "crater" in the water and a splatter radially outwards moving water up, over, and down the crater sides. This immediate outflow of water and the local elevation of the water's surface (Figure H-9) prevents oil from being entrained by the water jet as it moves through a slick. During the USCG ZRV Skimmer tests the water jets were moved into oil slicks at six knots in calm water and harbor chop with little or no oil entrainment beneath the jets. The effect of the rising air entrained by the jet is even more dramatic and longer lasting. An air bubble rising in a body of water will grow and increase in ascent velocity as it travels upwards. Water is pushed from the bubble's path and some is entrained in behind the bubble as it rises. As the bubble reaches the surface, before it bursts, it pushes the last level of water radially outward and brings the entrained water to the surface, which is also radially dissipated after the bubble bursts (Figure H-10). If the bubble is large enough or there are enough small ones, a sizable surface current can be produced. A good amount of air can be driven into the body of water by emitting a pressurized stream of water from a smooth pipe nozzle held above the surface of the water. This can be demonstrated by filling a glass with water at a sink. The action of air bubbles rising through water can be observed in a fish tank using a common air pump aerator. The movement of oil on the surface caused by the bubbles can be demonstrated by the movement of particles (e.g. fish food) on the surface of the tank.

Unlike the fish tank aerator, the water jet produces bubbles from about 4 inches in diameter to ones about 0.04 inches and smaller in diameter. The large bubbles rise quickly to produce the sudden, forceful surface current which moves the oil initially while the millions of small bubbles rise slowly to prevent the oil slick from spreading again.

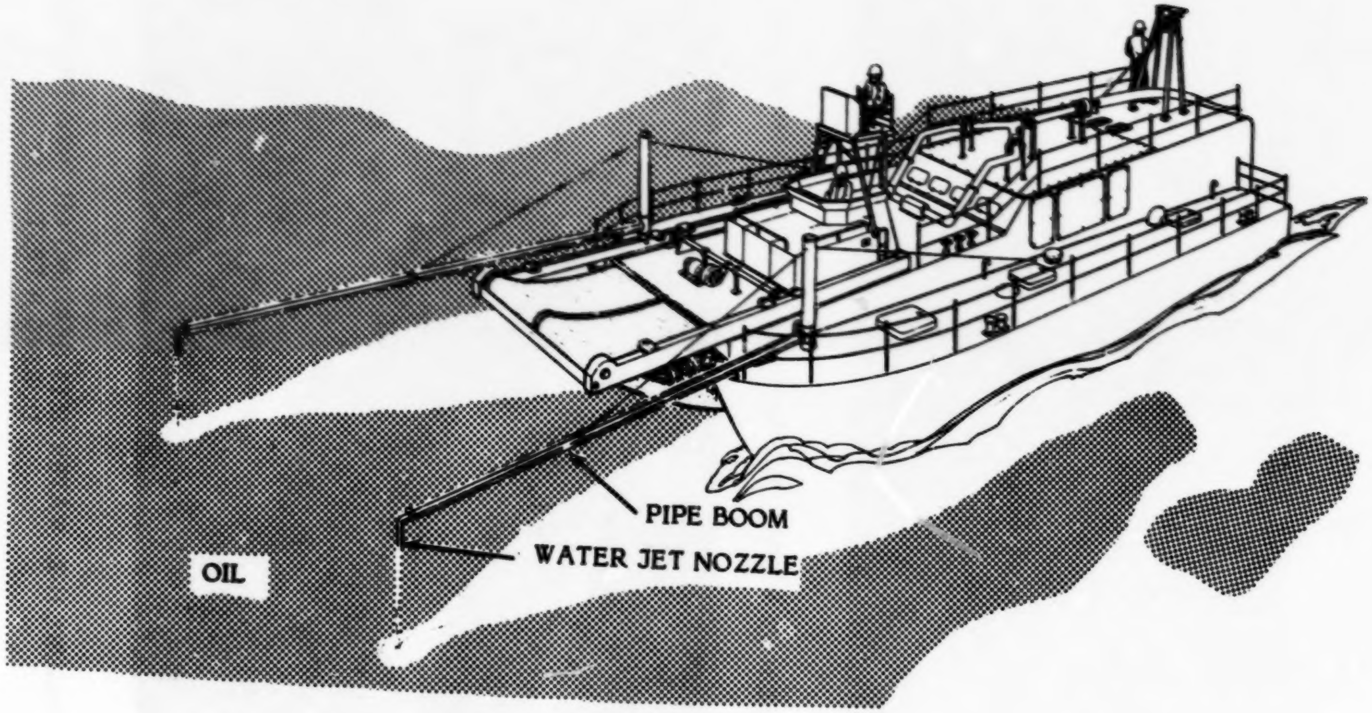

PIPE BOOM
WATER JET NOZZLE
OIL

FIGURE H-6. USCG ZRV SKIMMER USING WATER JETS TO SWEEP OIL.

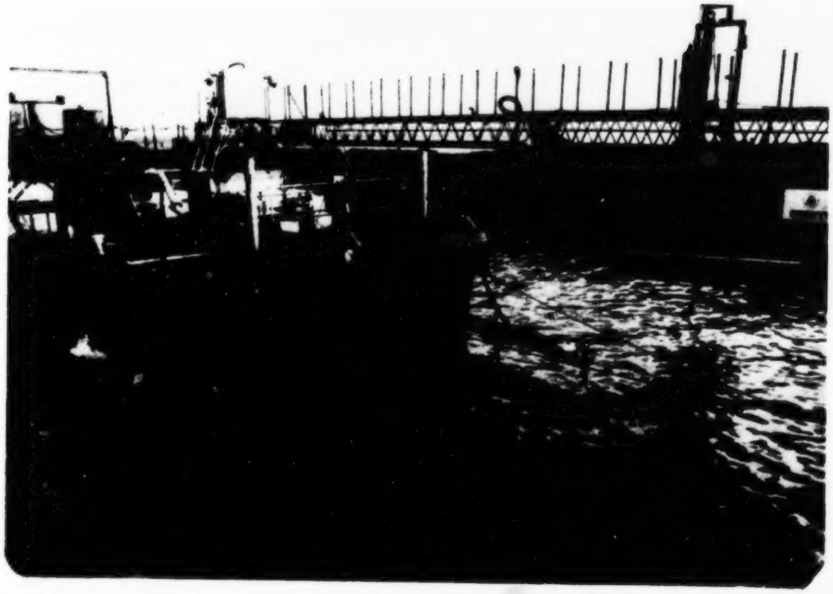


FIGURE H-7. WATER JETS MOUNTED ON THE SKIMMER AT OHMSETT.

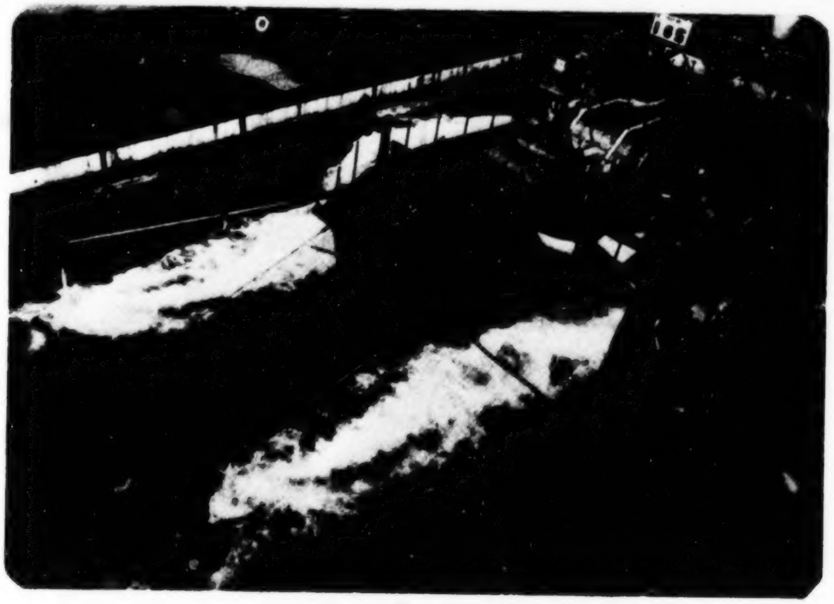


FIGURE H-8. WATER JETS HERDING OIL INTO THE SKIMMER DURING A TEST.

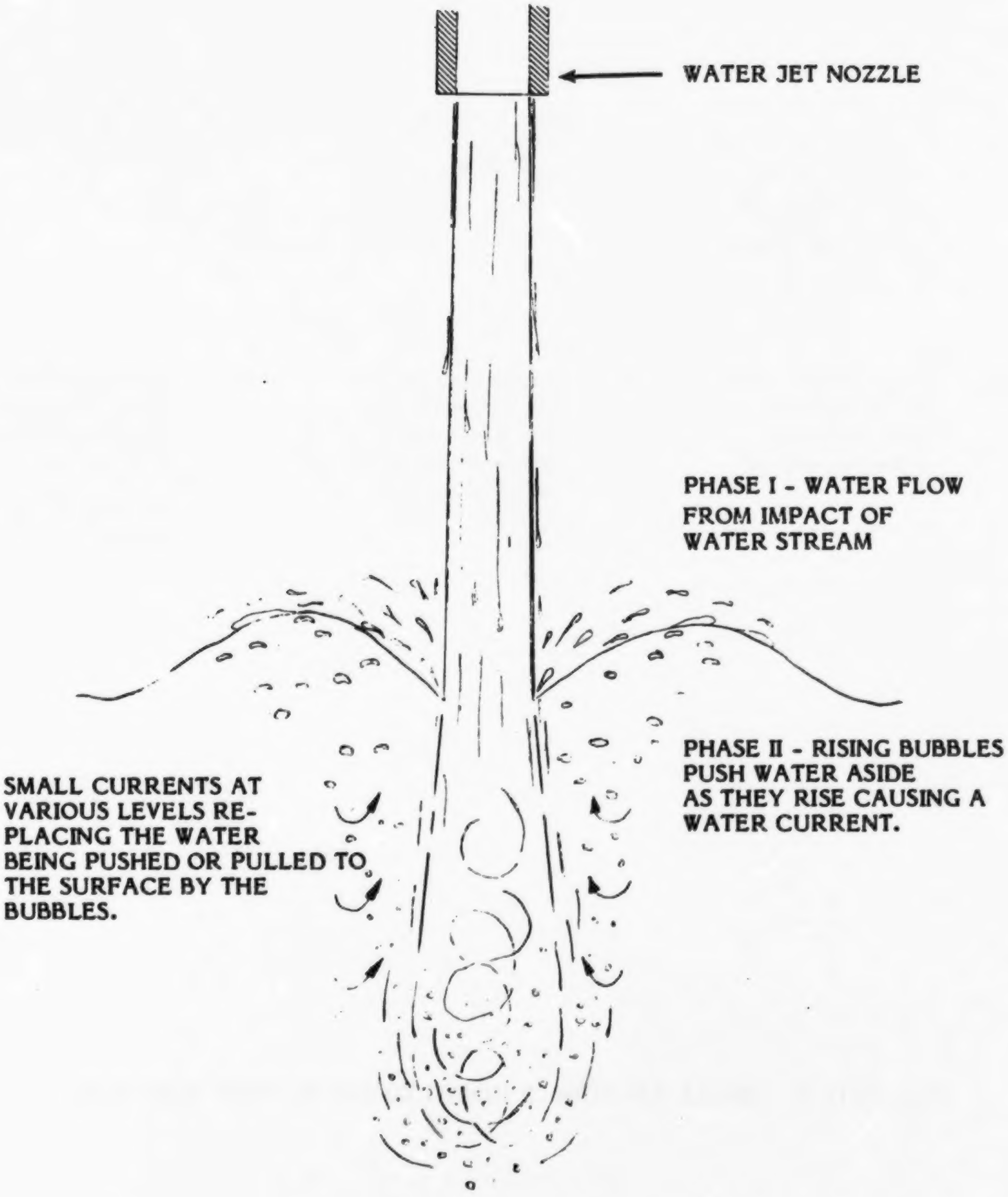
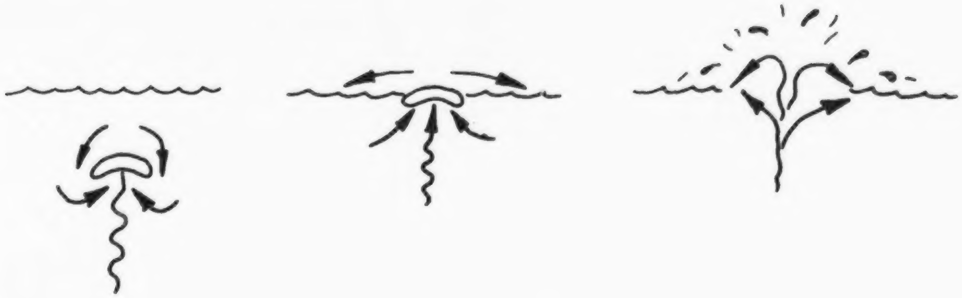

WATER JET NOZZLE
PHASE I - WATER FLOW FROM IMPACT OF WATER STREAM
PHASE II - RISING BUBBLES PUSH WATER ASIDE AS THEY RISE CAUSING A WATER CURRENT.
SMALL CURRENTS AT VARIOUS LEVELS REPLACING THE WATER BEING PUSHED OR PULLED TO THE SURFACE BY THE BUBBLES.

FIGURE H-9. SECTION VIEW OF WATER JET ACTION.



A. As air bubble rises water is pushed from on top and entrained behind.

B. As bubble reaches the surface the last water layer is pushed radially outward in the surface.

C. As the bubble bursts the water entrained beneath it is carried to the surface and also radially dissipated.

FIGURE H-10. SINGLE AIR BUBBLE RISING TO THE WATER'S SURFACE.

The water jet oil herding concept is simple, reliable in calm water and waves, and inexpensive. The system can be assembled from off-the-shelf hardware items, can be powered using a common shipboard fire pump, and does not employ environmentally harmful chemicals.

Water Jet Oil Herder - Test Set-Up

The water jet system mounted on the USCG ZRV Skimmer consisted of two 20-foot long, 3-inch diameter, reinforced alumimun pipe booms with fire hose connection inlets at the aft end and a 1-ft long, 3/4-inch diameter nozzle on the forward end. These booms were clamped to two vertical supports at the bow of the skimmer by a collar which permitted them to be splayed at different angles (Figures H-11 and H-12). The nozzle units could be directed forward or aft while the entire pipe boom could be rotated longitudinally to direct the nozzles towards or away from each other. Guy wires supported the booms and held them in place. The water jets were supplied with pressurized water via 1.5 inch diameter fire hoses. For most of the OHMSETT tests the fire pump on the main bridge supplied the pressurized water. The bridge pump could maintain a greater pressure at the nozzles than the fire pump onboard the skimmer. The main bridge pump was designed to deliver 500 gpm at 100 psi with the 40-horsepower electric motor directly connected to it. The skimmer's fire pump was designed to discharge 110 gpm and produce a dead head pressure of 100 psi using a hydraulic motor of 10 to 12 horsepower. Use of the larger pump allowed testing at higher tow speeds since the greater pressure of the jets impacted the surface harder and entrained more air. This produced a greater and farther-reaching surface current so the oil slick could be concentrated faster. Tests using the main bridge fire pump succeeded in converging an 18-ft wide slick into the skimmer at speeds up to 4 knots. The skimmer's fire pump supplied the water jets with sufficient power to work well at 2 knots.

For the skimmer tests, the nozzles were separated 18 ft or twice the width of the distance between the catamaran hulls. These tests, where all of the oil was converged from a 18 ft wide slick to a 9 feet wide slick, showed that the water jet system effectively doubled the sweep width of the skimmer.

OHMSETT TESTS

Objectives

The objectives of the OHMSETT tests were to demonstrate the air-jet and water-jet boom systems in conjunction with the ZRV skimmer; acquire operating experience with them; and identify and compare limits of performance for each boom system.

Test Procedure

Routine OHMSETT procedures were used throughout the skimmer/boom evaluation. Descriptions can be found in earlier sections of the report. Deviations from the procedures are indicated.

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[2] Ibid.

[3] Ibid.

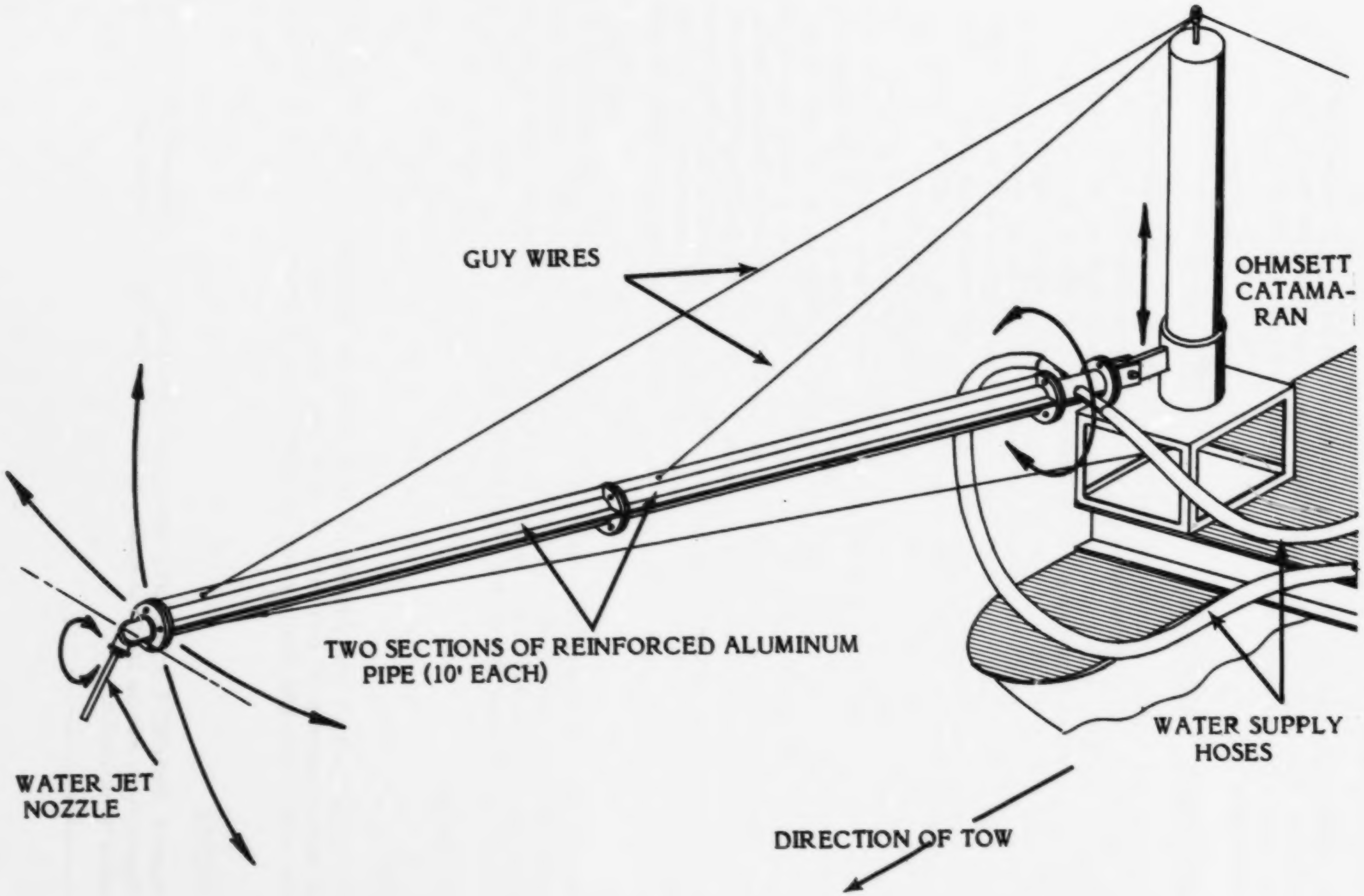

GUY WIRES
OHMSETT CATAMA-RAN
TWO SECTIONS OF REINFORCED ALUMINUM PIPE (10' EACH)
WATER JET NOZZLE
WATER SUPPLY HOSES
DIRECTION OF TOW

FIGURE H-11. USCG ZRV WATER JET BOOM MOUNTED ON THE OHMSETT CATAMARAN.

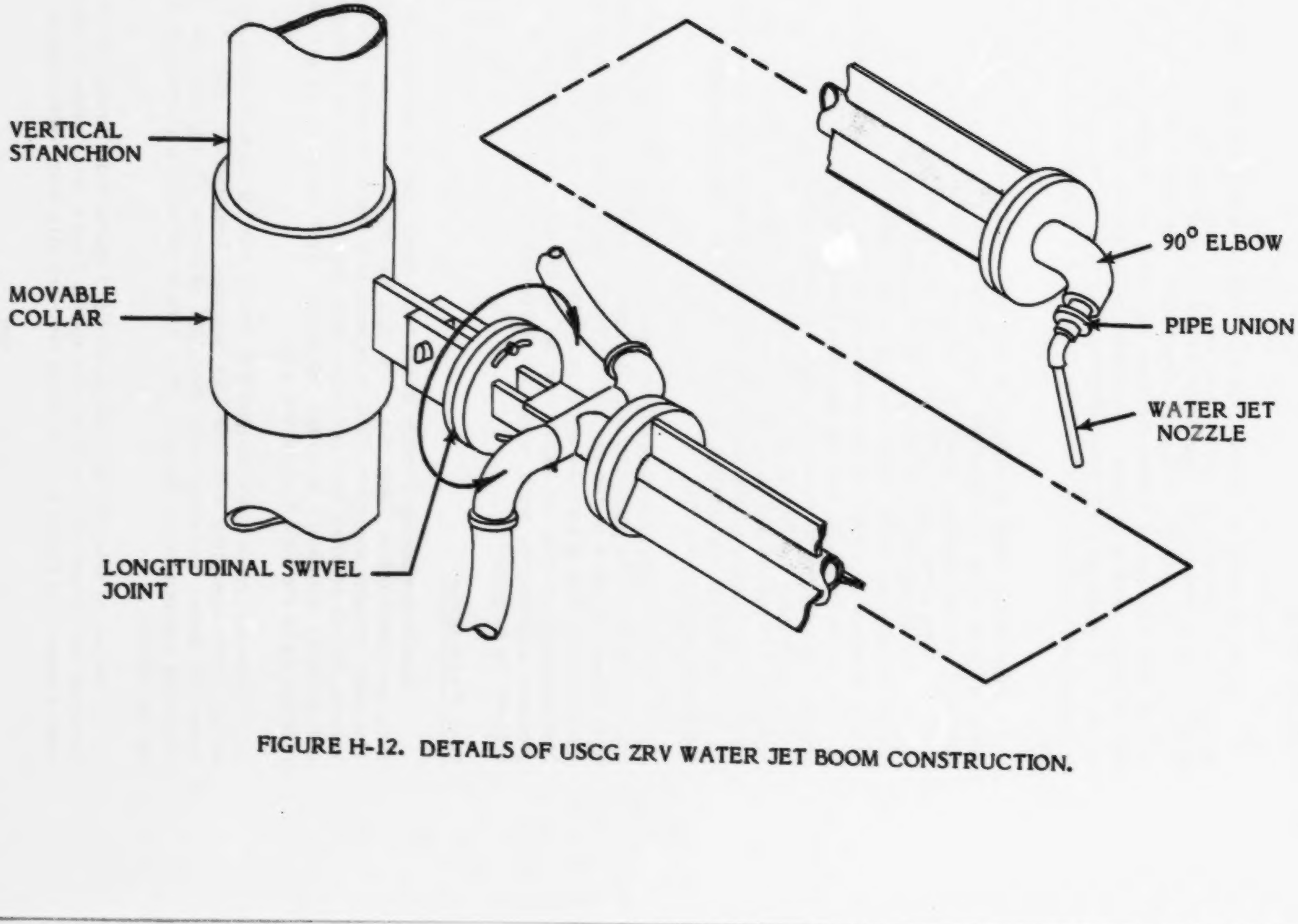

VERTICAL
STANCHION
MOVABLE
COLLAR
LONGITUDINAL SWIVEL
JOINT
90° ELBOW
PIPE UNION
WATER JET
NOZZLE

FIGURE H-12. DETAILS OF USCG ZRV WATER JET BOOM CONSTRUCTION.

Test Conditions

All boom tests were conducted with medium grade test oil at speeds from 2 to 6 knots with the majority of tests conducted at 4 knots. Water jet boom tests were run in calm water and harbor chop wave conditions while the air jet boom was tested in calm water only, per the designer's directions. The ZRV belt speed was, in all cases except Test 129, run at ½ knot less than the speed of the skimmer. Extender position was varied, depending on speed. Generally, at low speed, the extender position was set at about 53 inches and increased progressively to 65 inches at high speed. Settings of belt speed and extender position were based on the experience of previous tests in the series.

Distributed slick thickness for the boom tests was calculated to provide the same oil flow rates and average slick thicknesses as encountered by the skimmer operating without booms. Based on 16.5 foot maximum opening for the air-jet boom and 18 foot maximum opening for the water-jet, the slicks were distributed at 1.7 mm and 1.5 mm thickness respectively. This resulted in an average slick thickness of 3 mm at the skimmer inlet. Since the USCG was interested in doubling the sweep width of the skimmer by using a slick converging system, the water jet width was set at 18 ft. The air jet, however, was not set up to sweep greater than 16.5 ft. Thus the air jet system was required to move the edges of the oil slick 3.75 feet while the water jets had to move them 4.5 feet to get it into the skimmer. This gave the air jet system an apparent 17% advantage over the water jet system. Because of the different oil movement techniques of the tow systems and the inherent complexities of determining oil slick thickness distribution, a correction factor was not employed to account for the different sweep widths.

The slick approaching the boom was controlled to fall slightly within the boom opening. As the slick passed through the boom, a centerline water-jet (shown in Figure H-4) parted the slick at the skimmer entrance, to prevent oil loss down the center of the skimmer. This is because the twin 3.5 foot ZRV belts do not blanket the entire 9 foot entrance, leaving the center portion of the slick otherwise unrecoverable. Jet pressure adjustments were made for different test conditions on the basis of engineering judgment.

Data Presentation

Results pertaining directly to the boom tests, abstracted from the main body of data, are presented in Table H-1. The data has been rearranged according to speed. The table includes sea state, slick thickness, belt speed, extender position, precharge volume, and jet pressure (air- and water-jet). Measured value of throughput efficiency and recovery efficiency are also tabulated. Test numbers are provided for cross-referencing to the main body of the data.

Several columns are divided into three, one for each configuration tested; the air-jet boom operating with the ZRV skimmer (denoted on Table H-1 as A.J.), the water-jet boom operating with the ZRV skimmer (W.J.), and the ZRV skimmer operating independently (Indep.). This format provides a convenient way for comparing results.

Graphs of selected data are plotted in Figures H-13 through H-15. Figure H-13 presents throughput efficiency versus speed; Figure H-14 presents boom efficiency versus speed; and Figure H-15 presents recovery efficiency versus speed.

TABLE H-1. ZRV SKIMMER/BOOM TEST RESULTS

Speed	Test no.	Sea state	Slick(3) thickness mm	Throughput efficiency %	Recovery efficiency %	Extender position in.	Precharge volume gal	Jet pressure psi
A.J.x1.8								
2	128	C	3.2	27.6	32.0	53.5	10.0	55
2	129	C	3.2	38.0	35.0	53.5	2.9	55
3	130	C	3.1	45.6	26.0	53.5	10.0	55
4	139	C	3.2	13.9	29.0	52.8	11.1	55
4	140	C	3.1	48.9	24.0	52.8	11.1	35
4	141	C	3.1	56.9	31.0	52.8	11.1	30
4	131	C	3.1	41.4	42.0	53.5	11.9	55
4	132	C	3.1	50.4	33.0	53.5	11.9	55
4	133	C	3.1	35.5	38.0	53.5	24.0	40
4	134	C	3.2	55.4	52.0	53.5	8.9	30
4	135	C	3.1	46.6	42.0	53.5	21.9	35
6	137	C	3.1	52.0	30.0	54.1	0.0	55
6	138	C	2.9	29.0	12.0	65.6	0.0	55
W.J.x2.0								
2	154	C	2.8	79.4	73.0	53.5	6.1	40
2	167	C	3.0	69.4	29.0	54.3	7.9	35(4)
4	155	C	2.0	60.3	31.0	53.5	10.0	80
4	166	C	3.2	57.2	36.0	54.3	5.0	80
4	168	C	3.0	64.4	33.0	54.3	10.0	30(5)
4	160	C	3.0	61.5	34.0	59.4	11.1	80
4	158	2.26HC	3.0	56.5	24.0	59.4	6.1	80
4	159	1.57HC	3.0	59.4	28.0	59.4	6.1	80
4	165	2.26HC	3.2	63.1	28.0	63.6	0.0	80

(Continued)

TABLE H-1. (Continued)

Speed	Test no.	Sea state	Slick(3) thickness mm	Throughput efficiency %	Recovery efficiency %	Extender position in.	Precharge volume gal	Jet pressure psi
6	156	C	3.2	33.8	23.0	64.8	0.0	80
6	162	1.57HC	3.0	53.2	34.0	59.4	0.0	80
6	163	1.57HC	3.0	40.9	22.0	63.6	0.0	80
6	164	1.57HC	3.0	53.9	34.0	63.6	0.0	80
Indep.								
2	14	C	3.1	91.5	85.0	53.5	15.1	
3	15	C	3.1	82.5	58.0	53.5	20.9	
3	4	C	3.3	88.2	54.0	54.3	16.8	
4	12	C	3.1	84.5	57.0	53.5	14.0	
4	30	C	3.2	75.2	54.0	53.3	25.1	
4	17	C	3.0	70.4	55.0	53.5	16.1	
4	SD 20	C	2.5	74.6	65.0	54.3	20.7	
4	42	2.26HC	3.7	61.8	49.0	56.5	23.2	
4	146	2.26HC	3.2	49.5	34.0	65.4	0.0	
4	34	1.57HC	3.1	67.9	50.0	53.3	29.9	
4	36	1.57HC	3.0	61.7	47.0	53.3	33.3	
4	38	1.57HC	3.1	65.5	49.0	53.3	26.7	
4	11	1.57HC	3.2	68.4	54.0	53.5	20.7	
4	40	1.04HC	3.3	84.4	48.0	53.3	33.3	
4	113	1.18x30.8	3.0	33.5	35.0	63.0	10.3	
4	114	1.18x30.8	3.1	71.8	45.0	63.0	16.9	
4	116	1.18x30.8	3.0	76.0	48.0	63.0	12.9	

(Continued)

TABLE H-1. (Continued)

Speed	Test no.	Sea state	Slick(3) thickness mm	Throughput efficiency %	Recovery efficiency %	Extender position in.	Precharge volume gal	Jet pressure psi
6	25	C	2.8	50.9	48.0	53.5	0.0	
6	26	C	3.0	53.8	46.0	57.3	0.0	
6	119	C	3.0	72.6	37.0	60.0	0.0	
6	142	C	3.1	54.3	24.0	65.4	0.0	
6	143	C	3.1	56.3	27.0	65.4	0.0	
6	144	C	3.2	69.4	23.0	75.4	0.0	
6	120	C	3.0	70.1	48.0	65.6	0.0	
6	121	C	3.2	88.7	57.0	65.6	0.0	
6	170	1.57HC	3.1	81.1	56.0	63.9	0.0	

NOTES:

(1) The following notations are used in this table:

A.J. - ZRV Skimmer with Air-Jet Boom
W.J. - ZRV Skimmer with Water-Jet Boom
Indep. - ZRV Skimmer without Booms
C - Calm Water
HC - Harbor Chop - Preceding number indicates wave height in feet. Where two numbers appear, a regular wave was used. The first number is wave height in feet followed by the length in feet of the regular wave.

(2) All tests conducted at belt speeds equal to one-half knot less than skimmer speed, except Test 129 (2 knots) which was conducted at belt speed equal to the skimmer speed.

(3) Actual slick thickness upstream of boom determined by dividing tabulated values for A.J. and W.J. by 1.8 and 2.0, respectively.

(4) ZRV water pump used to supply the water jets.

(5) Four water jet nozzles used.

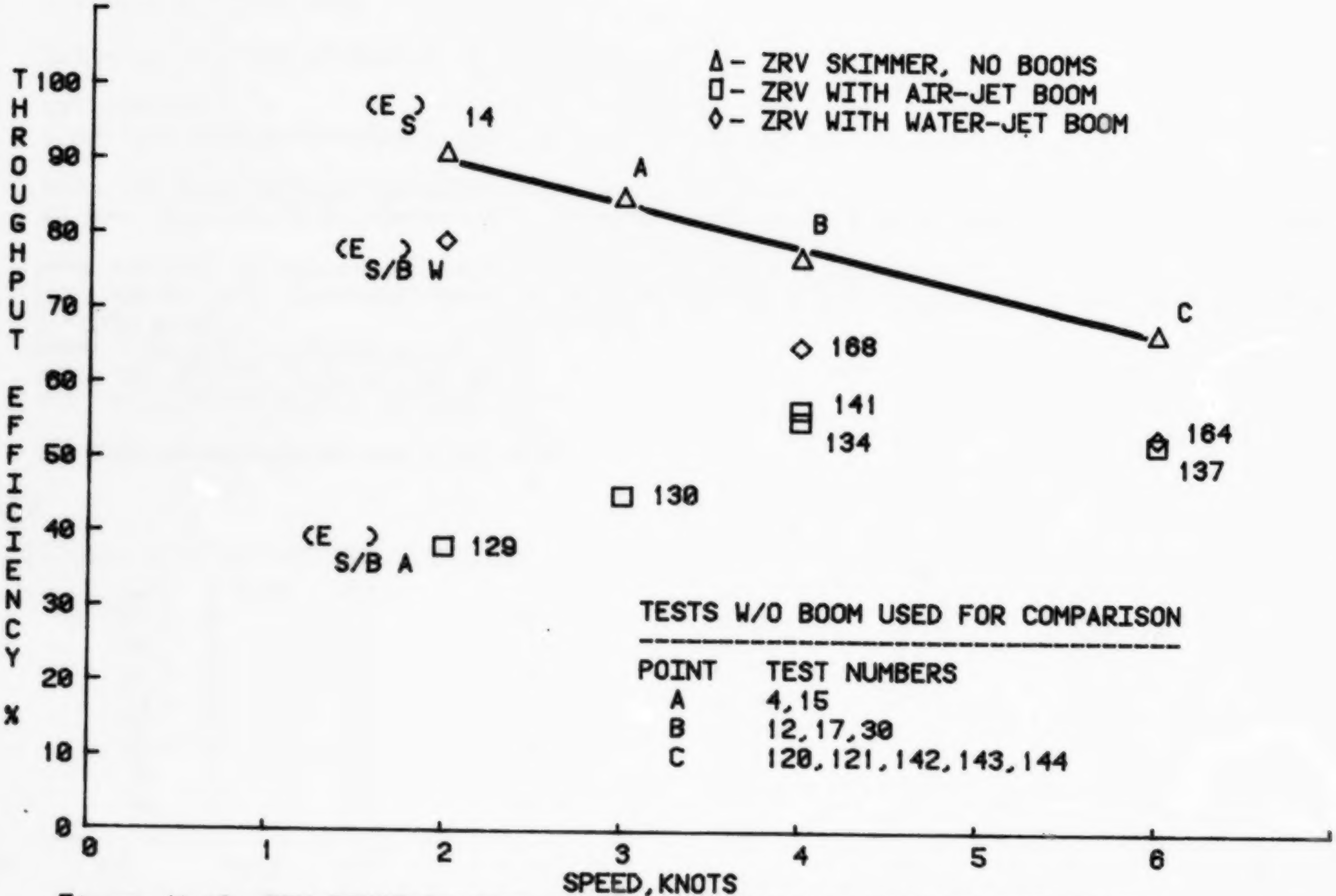
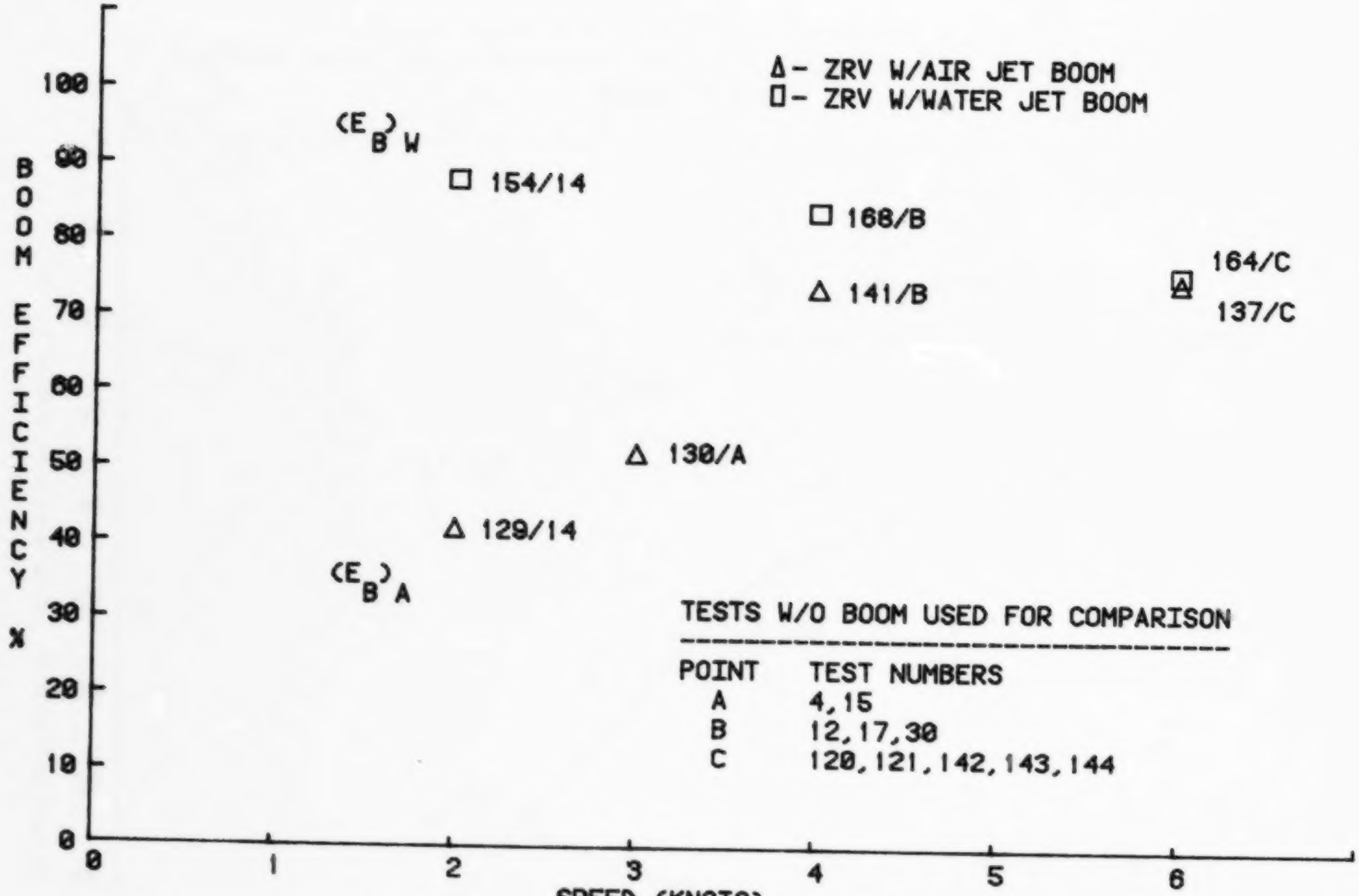


Figure H-13: ZRV-CONCENTRATION BOOM PERFORMANCE THROUGHPUT EFFICIENCY VS. SPEED IN MEDIUM OIL.



TESTS W/O BOOM USED FOR COMPARISON

POINT	TEST NUMBERS
A	4,15
B	12,17,30
C	120,121,142,143,144

Figure H-14: ZRV BOOM PERFORMANCE - MEDIUM OIL

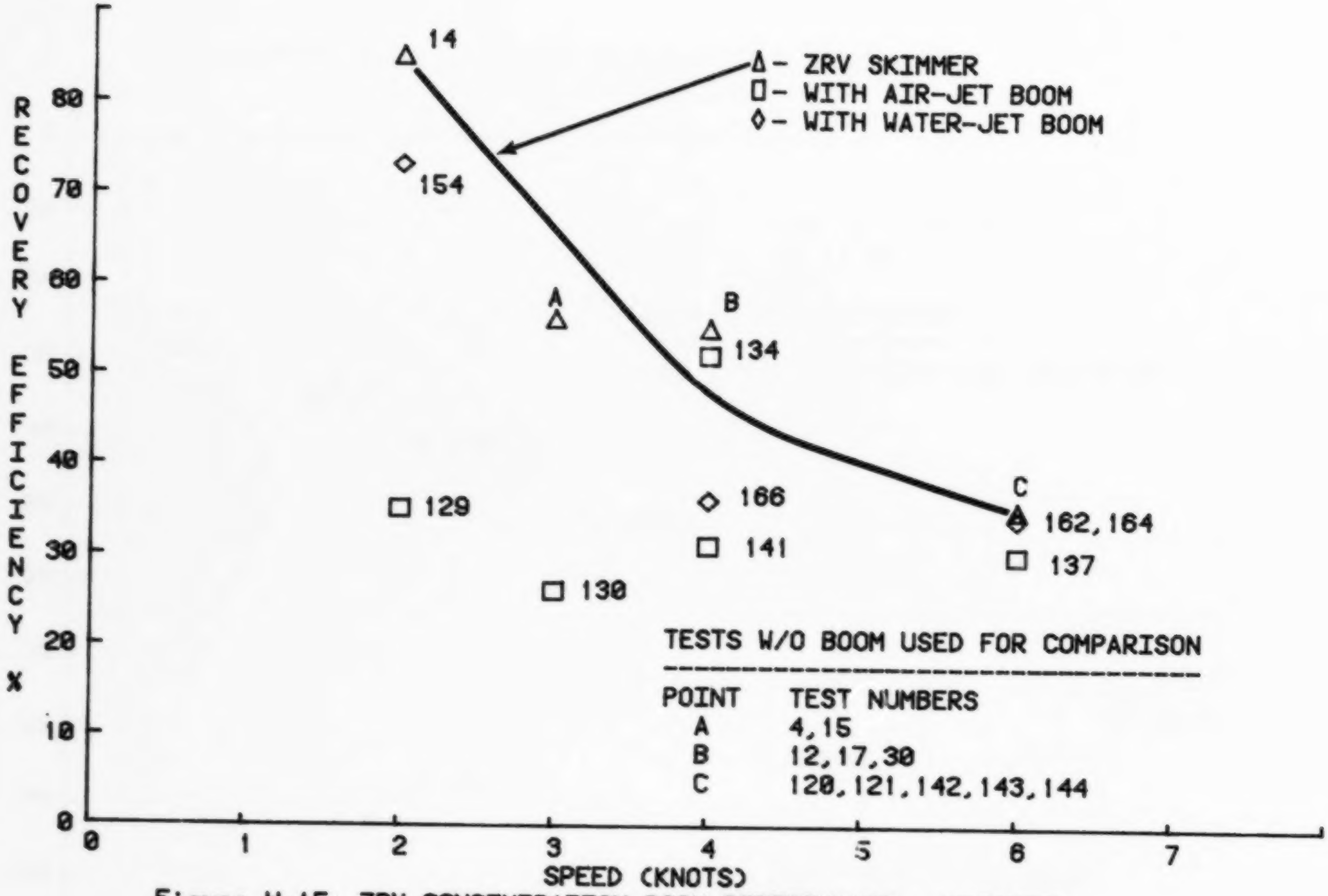


Figure H-15: ZRV CONCENTRATION BOOM PERFORMANCE - RECOVERY EFFICIENCY VS. SPEED WITH MEDIUM OIL

The data plotted for the ZRV skimmer operating independently is an arithmetic average of tests indicated. Each average is calculated for the best extender position at each speed. For example, at 6 knots, the average is taken for the 65.4-65.6 inch extender position. On the other hand, the data plotted for the boom tests are optimums at each speed (referenced test number is next to each data point). This was done because fewer repeat tests were done and more variables are involved. This is particularly true for the air-jet boom where pressures were changed.

Air-Jet Boom - Analysis of Results

The throughput efficiency results for the air-jet boom (Figure H-13) exhibit a general increase in efficiency with speed up to 4 or 5 knots. However, relative to water-jet booms' throughput efficiency, the air jet boom shows poorer efficiency, especially in the lower speed range. At higher speeds, the efficiency of the two tend to merge and are nearly equal at 6 knots. The proximity of the efficiencies of the two systems at the higher speeds was also due to the lesser sweep width of the air jet boom system.

The poorer performance of the air jet boom in the low speed range was caused by the boom being too forceful, driving the oncoming oil slick close to the skimmer centerline and causing an unfavorable slick thickness distribution. The forceful air currents also threw water droplets on top of the oil slick which could have affected skimmer performance. The tests clearly indicated that up to three knots, there is no visible loss of oil around the boom ($L_B = 0$). From Figure H-14, the slick thickness distribution, δ, is .42 at 2 knots, increasing to .53 at 3 knots (since $Q_1 = Q_2$).

As a result of the poor performance at 2 and 3 knots, and similar results at 4 knots (see Test 131), the air pressure supplied to the boom was reduced from 55 psi to 35 psi (see Test 140), and then again reduced to 30 psi (Tests 141 and 134). Major improvements in performance were achieved. Tests 141 and 134, run at 4 kts provided the best results, yielding skimmer throughput efficiency of 56% and boom efficiency of .73. Oil loss was observed, but did not appear to be major. Using the results of the former air-jet boom tests, the ratio of Q_2/Q_1 is estimated to be 96% (by considering that the oil directly ahead of the boom is diverted with 90% efficiency, see reference 4).

Therefore, the slick thickness distribution is about .76, which represents a further increase from 3 knots. High recovery efficiency (Figure H-15) was also measured for Test 134, which may serve as an indication of the improved slick thickness distribution.

At 6 knots, the air jet boom exhibited major loss. The actual extent is, however, not known because these measurements are extremely difficult to obtain.

If a worst case situation is assumed, where no oil is diverted by the boom, it can be shown that the theoretical boom efficiency equals .55 (.50 for the water jet boom). This is based on the concept that the boom has little or no influence on the oncoming slick, such that $\delta = 1$ and the ratio of Q_2/Q_1 is equivalent to the ratio of the skimmer entrance to the boom opening (i.e., 9/16.5 = .55).

According to Figure H-14, however, this worst case boom efficiency (.55) is well below the .76 efficiency reported. But, as shall be seen, the plotted value is somewhat misleading because of the method used in calculation.

In particular, the boom efficiency calculation is only accurate if the oil losses are relatively small, so that the reduction of Q_2 and subsequently the oil slick thickness does not significantly increase the skimmer's throughput efficiency.

At lower speeds (with nominal loss), the slick is about 3 mm thick at the skimmer entrance, but under the worst case scenario, the slick is reduced to 1.7 mm.

In turn, a major change in throughput efficiency does occur. Test 21, (Table C-1) in fact, suggests that the throughput efficiency for the worst case scenario is near 100%.

Consequently, if we calculate a modified boom efficiency based upon the throughput efficiency of Test 137 (see Figures H-13 and H-14, 6 knots) comparing it to the 100% throughput efficiency of test 21, the actual boom efficiency is very close to .55. Clearly, this suggests that little or no oil is being diverted, making the air jet boom of little apparent value at 6 knots.

Water Jet Boom - Analysis of Results

The water jet boom performed as expected considering the results of previous test programs (see references 2 and 3). The efficiency of the system to converge an oil slick declined with increasing tow speed. The decline in water jet performance parallels that of the ZRV skimmer's performance which indicates there are not any drastic effects on oil slick distribution due to tow speed. The slick thickness factor, w, can be determined for tests at two and four knots because no oil was seen to be lost from the booms at those speeds. At two knots, w is 0.87 while at four knots, w is 0.84. The proximity with these two values indicates that tow speed does not greatly effect oil slick thickness distribution produced by the water jets. The increase of water pressure from 40 psi at two knots to 80 psi at 4 knots did not significantly affect w. This seems to indicate that an increase in jet ferocity does not greatly affect oil entrainment. However, an inherent oil slick anomaly is probably produced (i.e. thicker oil slick at the outside edges of the converged slick) by the water jets at all tow speeds and water pressures. At 6 knots oil loss was noted extending outboard of the catamaran hulls about 1 foot so w cannot be determined.

Using the same method of calculation performed for the air jet boom in determining a modified boom efficiency at the six knot tow speed yields an efficiency of about 54% for the water jet. This is only slightly above the worst case efficiency of 50%, which indicates that at a sweep width of 18 ft the water jet system does not significantly contribute to skimmer performance at 6 knots. Here, however, is where the difference in sweep widths of the two systems should be noted so that no blanket assumption is made that both systems fail at 6 knots. Oil losses from the water jet system did not occur because the system did not move the oil but rather because it did not move the oil far enough. Whereas oil losses occurred over the entire length of the air jet cylinders as oil passed beneath them at 6 knots, the water jet system lost oil only directly outboard of the skimmer inlet. Given the reduced sweep width which was allowed the air jet system, the water jet system would have performed better at 6 knots.

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(3)This is consistent with previous tests of the air-jet boom in its original configuration, where losses occurred only beyond 3 knots, Reference 1.

(4)For review (see Figure H-1), the boom efficiency is the quotient of skimmer throughput efficiency with booms to skimmer throughput efficiency without booms.

The water jets were directed vertically downward for calm water and wave tests. A better performance in calm water could have been obtained if the jets were angled in towards each other. This would have used the horizontal component of force developed by the jets and still entrained air to produce a current to move the oil. However, it was felt that the system should be tested in the configuration it will be used in the field in all wave conditions.

Conclusions

The water jet system was chosen to be incorporated into the USCG ZRV oil recovery system.

The water jet system proved to be superior to the air jet system in many ways. It outperformed the air jet system at all speeds. It operated effectively in waves without modification. Power and machinery requirements for the water jet system were much less than the air jet system. Based upon test set-up requirements at OHMSETT, the adaption of a water jet system to other skimmers would be easier than adaption of an air jet system. Materials for construction of a water jet system would be less expensive, more easily available and more rugged than those required for an air jet system.

APPENDIX I

ZRV WAVE RESPONSE DATA

The ZRV skimmer motion response is detailed in Table I-1 and Figures I-1, I-2, and I-3. Only three data points were taken in the rolling condition due to the need to get the skimmer out of the test tank. There is uncertainty in the accuracy of the roll data, but the pitch data is good.

The skimmer's motions are generally lower in magnitude than the waves causing the motions. Therefore, the maximum pitch angle of the skimmer is less than the maximum wave slope and accelerations are similarly lower. There is not a significant magnification factor in the motions at a wave frequency near the natural frequency of the boat.

In general, the motions measured appear to be correct based on observations with the skimmer in waves. The skimmer is very stable and does not pitch or roll readily. It is a sea kindly boat and does not have a tendency toward snap rolls or severe accelerations.

TABLE I-1. ZRV WAVE RESPONSE DATA

Test No.	Wave Length L_{wave} Feet Nominal	Frequency W_{wave} Cycles/Min Nominal	Frequency W_{wave} Cycles/Min Measured	Wave Amplitude H_{wave} Feet Measured	Frequency W_{ZRV} Cycles/Min Measured	Pitch Amplitude P_{ZRV} Degrees Measured	Acceleration Amplitude A_{ZRV} Ft/sec^2 Measured
						Pitch	
1	10.3	30	28.9	.46	27	.66	0.58
2	13.6	26	26.1	.49	25	.74	0.61
3	30.7	17	16.9	.3	16.8	1.19	0.29
4	46.1	13	13.6	.23	13.5	.94	0.26
5	70.2	10	9.8	.2	9.8	.41	.13
6*	70.2	10	10.0	.2	10.0	.45	.13
7	94.5	8	7.8	.13	8.0	.32	.07
						Roll	
8	10.3	30	28.1	.39	29.8	1.42	1.51
9	13.6	26	25.9	.36	25.4	2.53	1.55
10	38.1	15	14.8	.3	15.1	2.85	0.35

*Test No. 6 is a repeat of Test No. 5

TABLE I-1. (Continued)

Test No.	L_{WAVE}/L_{ZRV} L_{ZRV} = 46 Feet	Wave Slope Degrees P_{Wave}	P_{ZRV}/P_{WAVE}	Acceleration Amplitude (A_{Wave}) (Ft/Sec^2)	A_{ZRV}/A_{WAVE}
1	.223	16.10	.041	4.2	.138
2	.297	12.98	.057	3.67	.166
3	.668	3.46	.344	.93	.312
4	1.003	1.79	.525	.47	.549
5	1.527	1.01	.406	.21	.614
6	1.527	1.01	.446	.22	.591
7	2.054	.50	.640	.09	.741
	L_{Wave}/B_{ZRV} B_{ZRV} = 22 Feet				
8	.467	13.80	.103	3.41	.444
9	.621	9.52	.266	2.66	.582
10	1.733	2.79	1.02	.71	.500

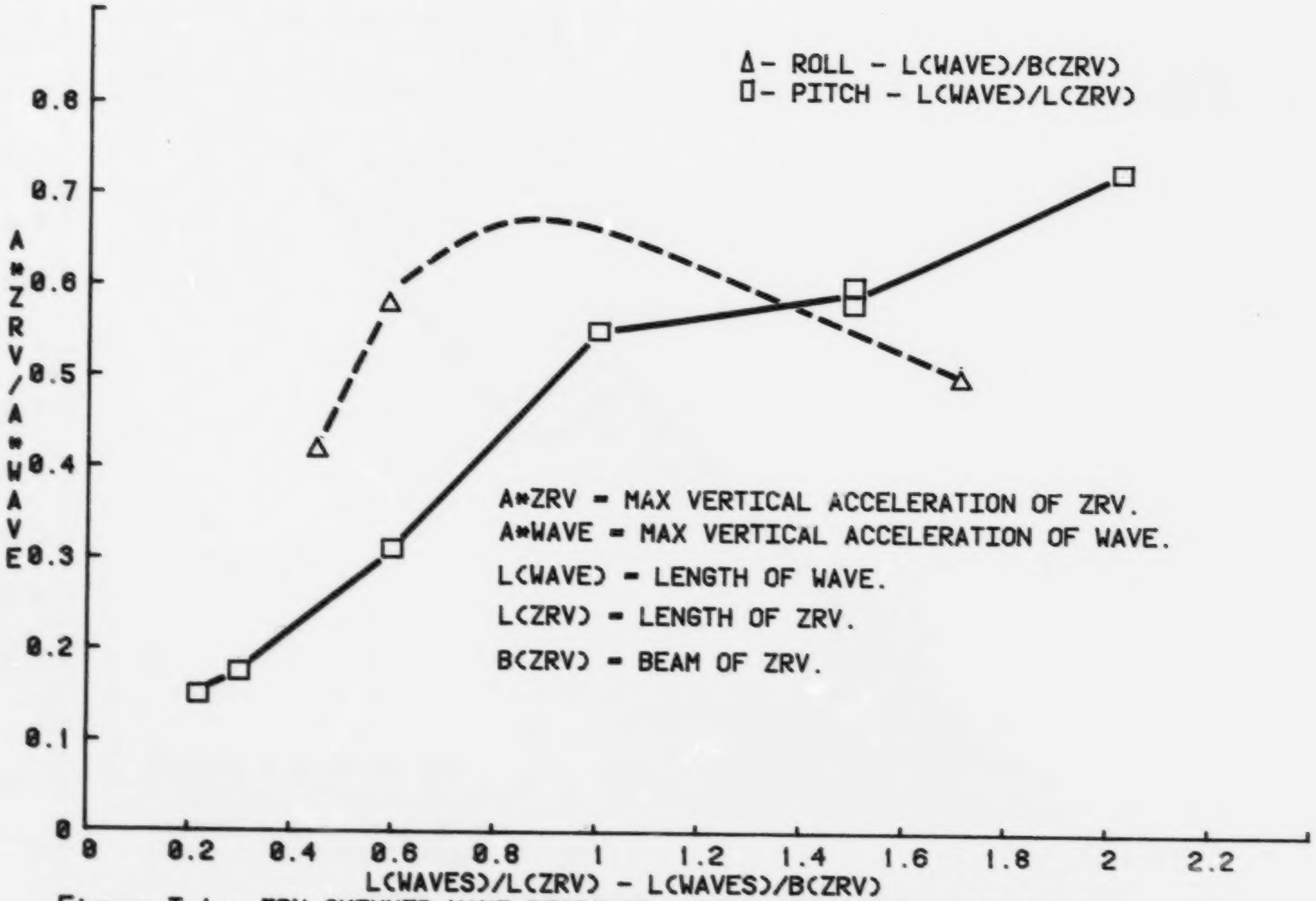

Figure I-1 : ZRV SKIMMER WAVE RESPONSE - ROLL AND PITCH ACCELERATION.

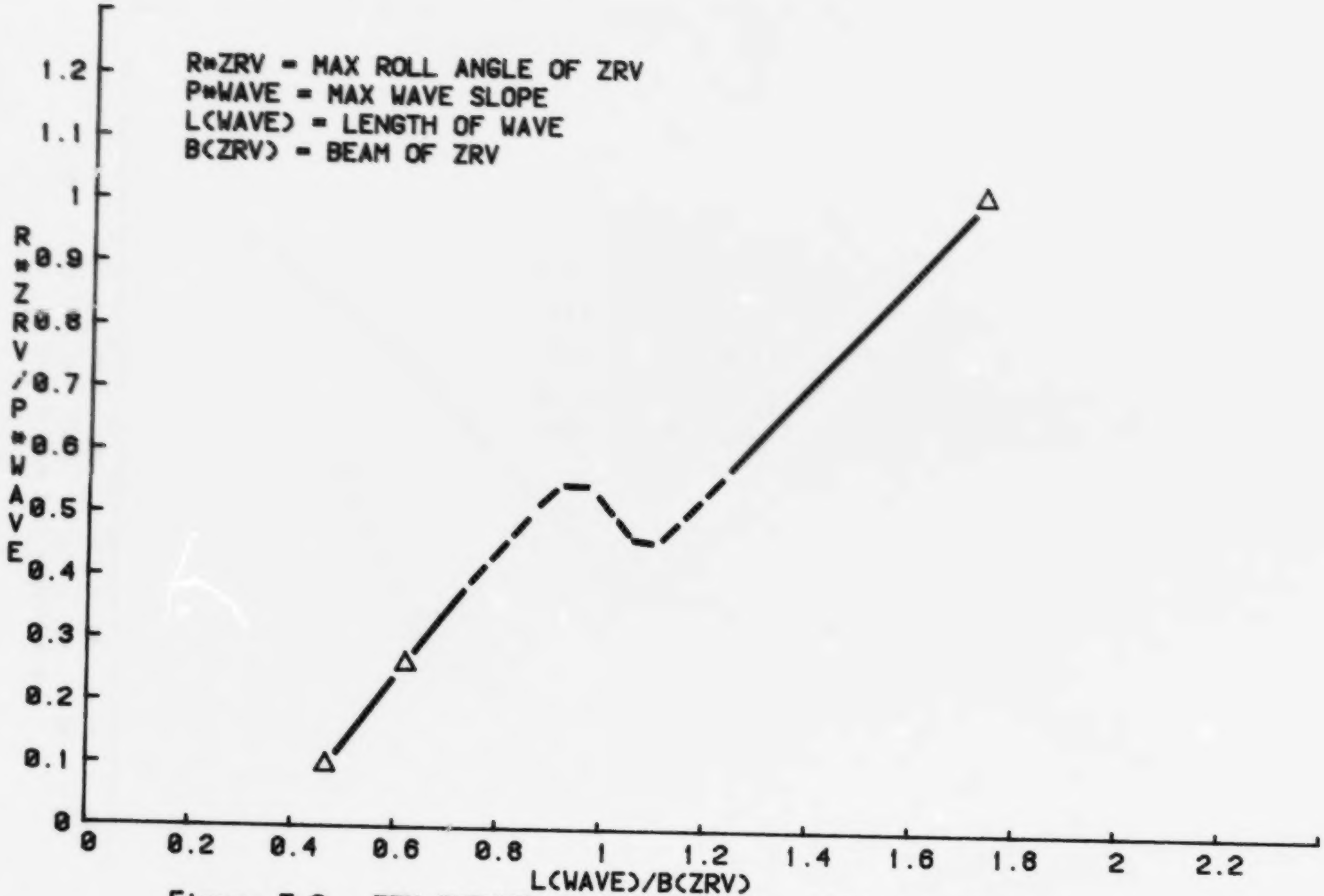

Figure I-2 : ZRV SKIMMER WAVE RESPONSE - ROLL AMPLITUDE.

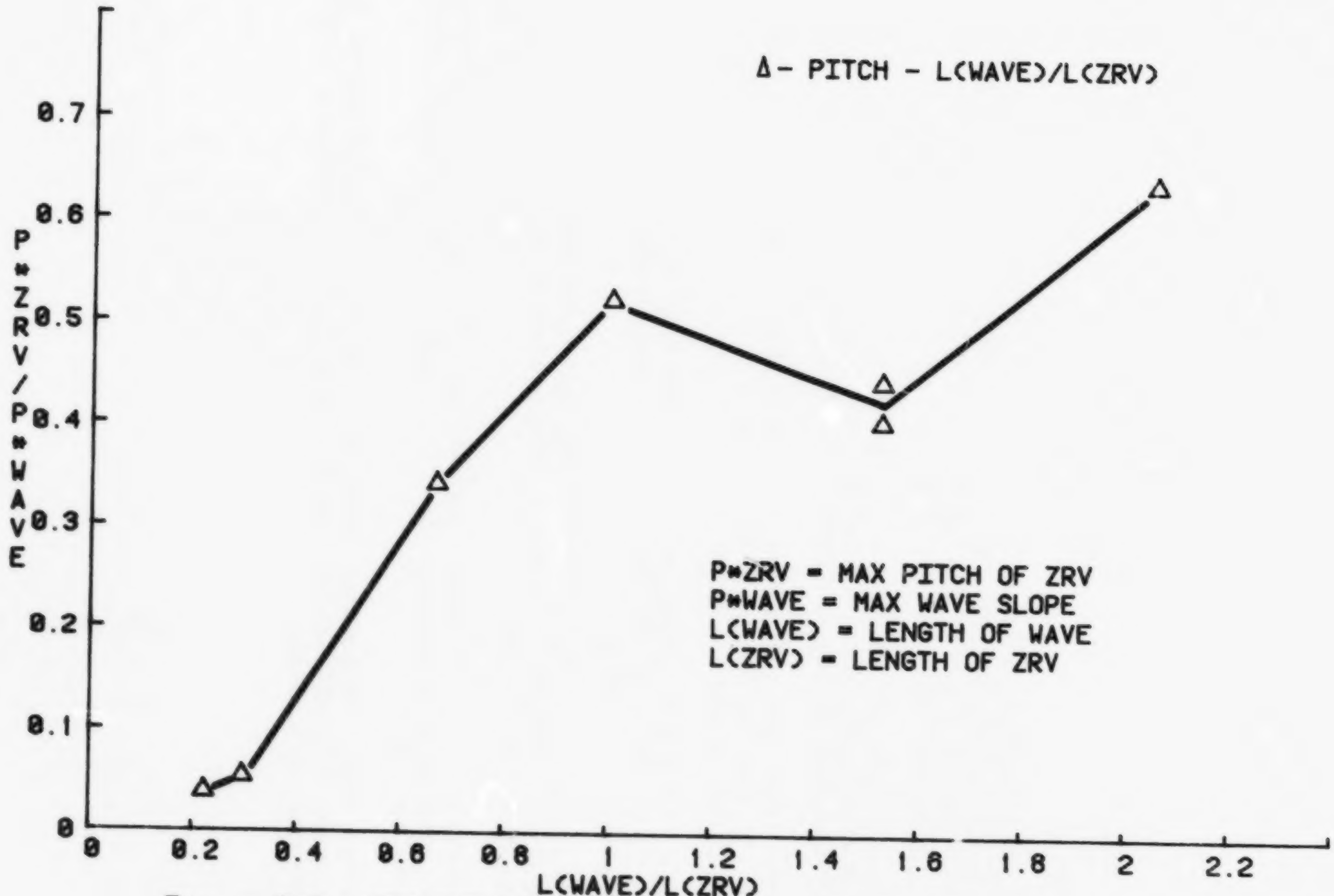

Figure I-3 : ZRV SKIMMER WAVE RESPONSE - PITCH AMPLITUDE

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